2019

Impact of a Winter Rye Cover Crop on Edge-of-Field Nutrient Losses and Corn Silage Production

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IMPACT OF A WINTER RYE COVER CROP ON EDGE-OF-FIELD NUTRIENT LOSSES AND CORN SILAGE PRODUCTION

A Thesis Presented

by

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to

The Faculty of the Graduate College

of

The University of Vermont

In Partial Fulfillment of the Requirements
for the Degree of Master of Science
Specializing in Plant and Soil Science

May, 2019

Defense Date: Nov 8th, 2018
Defense Examination Committee

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ABSTRACT

Cover crops have the potential to reduce environmental impacts of corn production. The objective of this study was to quantify differences in nitrogen (N) and phosphorus (P) loading between corn plots with or without a winter rye cover crop (*Secale cerale*). Four field plots (30 x 46 m) in Chazy, NY with edge-of-field monitoring were used for the study. Two plots were randomly assigned a rye cover crop treatment and planted with a grain drill at a rate of 112 kg ha^{-1} after corn silage harvest in 2015 and 2016. Continuous water flows were monitored from surface runoff and tile drain hydrologic pathways during runoff events. Soluble reactive P (SRP), total P (TP), nitrate-N, total N (TN), and total suspended solids (TSS) concentrations were measured and multiplied by runoff volumes to estimate nutrient export. Surface runoff from rye plots had lower nutrient loss compared to control plots. Cumulative nitrate-N exports were similar between treatments (15.7 vs. 14.8 kg nitrate-N ha^{-1} for rye and control, respectively). Cumulative TN exports were numerically higher for control plots compared to rye plots, (18.8 vs. 21.4 kg TN ha^{-1}). Cumulative TP and SRP exports (surface + tile) for rye were 2.2 and 3-fold greater than control plots, (0.51 vs. 1.19 kg TP ha^{-1} and 0.33 vs. 0.96 kg SRP ha^{-1}). Total P and SRP loads in surface runoff were 3.0-fold greater for control plots compared to rye plots (0.36 vs. 1.12 kg TP ha^{-1} and 0.32 vs. 0.94 kg SRP ha^{-1}). TSS load in surface runoff was numerically higher for control plots compared to rye (5.7 vs. 20.6 kg ha^{-1}). Cumulative surface runoff was 1.8-fold greater in control plots compared to rye plots (112.6 mm vs. 207.7 mm), while cumulative tile runoff was numerically higher in rye plots compared to control (83.2 mm vs. 66.1mm). Snowmelt events contributed the majority of phosphorus losses (96% of SRP and 92% of TP), emphasizing the need to implement management techniques that reduce P transport risk during the non-growing season. Winter rye reduced snowmelt TP export by 3-fold compared to the control plots (0.33 kg TP ha^{-1} and 1.03 kg TP ha^{-1}). The winter rye cover crop planted after corn silage harvest effectively reduced erosion and P transport in surface water runoff compared to corn silage left fallow after harvest. In addition to significantly reducing P exports, farms have the option of harvesting rye as a forage crop and double cropping with corn. In this way, more total forage is possible for the farm in addition to offering environmental conservation and water quality benefits.

ACKNOWLEDGMENTS

I would like to thank the University of Vermont's Department of Plant and Soil Science and my graduate committee members, Dr. Donald Ross, Dr. Julia Perdrial, Dr. Joseph Gorres, and Dr. Eric Young. Their guidance was crucial to the completion of this research.

I would also like to thank the William H. Miner Agricultural Research Institute and the Northern New York Agricultural Development Program, both of which provided funding to complete this project. I would also like to thank all of the employees at the Miner Institute who taught and supported me throughout graduate school; especially Dr. Eric Young, Steven Kramer, Laura Klaiber, and Charlie Hacker.

I would also like to thank my family who supported me through all of my education, especially my grandfather who pushed me to pursue a masters.

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1.1. Environmental Impacts of Agriculture

The ever-growing world population requires farmers to produce more food from the land they have. This requires farmers to be more efficient with the natural resources they have on their farms, namely, soil, nutrients, and water. Fertilizer is often a necessary requirement to obtain the yields needed to maintain profits and provide adequate food for the growing population. If these fertilizers, like phosphorus (P) and nitrogen (N), are applied in excess, they have the potential to be exported from the field in runoff. Eventually entering surface and ground water contributing to eutrophication (Daniel et al., 1998; Ryther and Dunstan, 1971). Eroded sediment originating from crop fields can enter surface waters and block sunlight, limiting the growth of aquatic plants and harming macro-invertebrates (Jones et al., 2012). When fine sediments reach slower moving waters like lakes and large rivers, settling occurs and may require periodic dredging, which is expensive and has its own environmental problems (Grimes, 1980). Soil erosion is the main pathway for P loss from agricultural fields (Sharpley et al., 1996). Erosion is also an important loss pathway for soil organic carbon (SOC), with as much as 44% of SOC mobilized through erosion is lost from the field (Polyakov and Lal, 2008).

Phosphorus pollution can cause algae blooms in fresh water systems, while excessive N can increase the potential for algae blooms in salt and brackish water. These algae blooms have the potential to produce harmful toxins. In addition, when the algae die, microbes begin the process of decomposition depleting oxygen; through this process hypoxic zones are created that can cause fish die offs (Diaz and Rosenberg, 2008; Foy, 2005). Another consequence of the lack of oxygen at the bottom of the lake and in the sediment is the release of P from sediment once it becomes anaerobic; this once bound-P re-enters the water column and is brought back to the surface, where it is available for algae to reuse (Smith et al., 2011). This process of algae growth, death/decay, results in the creation of hypoxic zones, and sediment bound P release perpetuates the eutrophication problem indefinitely even after all inputs are stopped. Whereas P has no known health risks, elevated nitrate in drinking water can cause methemoglobinemia in infants (resulting in the blood not being able to carry oxygen) and has been linked to higher cancer rates in some studies. For this reason, EPA set a limit of 10 mg nitrate-N L^{-1} for nitrate in drinking water (Knobeloch et al., 2000). Nitrogen is also a costly fertilizer. When approximately 50% of the applied fertilizer N is lost from agricultural landscapes (Tonitto et al., 2006) it is not only a detriment to the environment, but also a large cost for the farmer.

The above-mentioned effects of agriculture are all heightened by climate change. With a changing climate, there has been an increase in the intensity of rainfall (Rosenzweig et al., 2001). Erosion potential from rainfall is determined more by the intensity (e.g. amount/time) than by the total volume (Wischmeier, 1959). Weather patterns are also changing so that extreme weather events are becoming more commonplace. Larger and more intense rainfall events are becoming increasingly frequent. This shift in weather patterns is also making some places wetter while others drier, extending droughts or contributing to other disasters such as flooding and mudslides. Due to this, it is essential to use techniques in agriculture that will enhance the soil water storage capacity and reduce erosion. Increasing soil water storage capacity can reduce the risk of flooding as well as reducing the water stress associated with drought (Basche et al., 2016). Incorporating the use of cover crops into annual crop rotations has the potential to reduce soil and nutrient loss to surface and subsurface waters. A cover crop can be defined as a crop grown for the protection and enrichment of the soil and is typically grown between successive annual production crops like corn silage or grain (NRCS, 2014). Research has demonstrated that a winter cover crop growing when fields typically remain fallow can substantially reduce these pollutants leaving the field (Sharpley, 1991; Tonitto et al., 2006). A winter rye cover crop can also be an environmental and economic benefit to the farmer if harvested as a hay crop forage prior to planting an annual crop such as corn.

1.1.1. Dairy Farming in the Lake Champlain Basin

Lake Champlain is currently experiencing elevated P concentrations that are leading to recurrent algae blooms, some of which may be toxic, particularly in shallow portions of the lake (Smeltzer et al., 2012). There is an estimate that 38% of the total P entering the lake is from agriculture and 46% from urban environments. In-lake cycling of P also contributes to the overall amount of P in the lake, however the amount added through internal cycling is currently unknown (LCBP, 2018a). Dairy farming is the dominant form of agriculture in the Lake Champlain Basin (LCB) and corn silage is a major crop used to feed dairy cows. Work has been done in the LCB to lower the amount of P in dairy manure by optimizing P sources in dairy rations and precision feeding (Cotanch et al., 2003), however dairy manure remains an important source of P applied to farm fields.

In the 1990's systematic water quality monitoring began in earnest in Lake Champlain. To date, P concentrations are not trending downwards and in some instances continuing to increase (Smeltzer et al., 2009). Due to continued impaired water quality of Lake Champlain, EPA developed total maximum daily loads (TMDL) for the lake and its sub watersheds in an effort to better target critical source areas of P loss. A TMDL is an estimate of how much of a particular nutrient a water body can receive without impairing vital uses. With phase 1 of this TMDL, technical and financial assistance is available to farmers to implement practices that will limit P loss from agricultural fields (LCBP, 2018b). One of the practices that offers a financial incentive and assistance is cover crops. Here in the northeast a typical rotation for a dairy farm would be corn silage followed by hay. Typically, after the harvest of corn silage, the fields would be left fallow and manure is generally spread on the surface and may or may not be incorporated into the soil before winter. Funding is available for farmers to implement a cover crop into their rotation to help keep soil and nutrients on the field through the non-growing season.

1.1. Soil health benefits derived from cover crops

Soil is fundamental to life on Earth. Without a healthy soil, crops needed for survival will struggle to thrive without an excessive amount of inputs. The Natural Resources Conservation Service (NRCS) defines soil health as "…the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals and humans" (NRCS, 2012). Characteristics of a healthy soil include good soil tilth, sufficient rooting depth, good water storage and drainage, sufficient supply of nutrients, small populations of plant pathogens and insect pests, large population of beneficial organisms, low weed pressure, and a resistance to degradation (Moebius-Clune, 2016). Soil quality is also part of soil health but refers to the intrinsic soil physical and chemical aspects affecting plant growth. Dynamic soil quality is synonymous with the contemporary term ‘soil health’, which refers to the sum total of biological, chemical, and physical factors affecting plant growth and our ability to manage these processes to maximize agronomic outputs and ecosystem services.

1.1.1. Soil Physical Properties and Carbon

Soil with a good tilth is rich in organic matter, crumbly, has no large and hard clods, and is well structured. Soil compaction and poor aggregation are two constraints that affect soil physical properties and compromise soil health. Soil compaction can reduce root growth, decreased infiltration, produce higher rates of surface runoff, reduce water storage and limit nutrient access from roots. Poor aggregation is caused by intensive tillage, low organic matter additions to the soil, and a low root density and lack of living roots throughout the year. Poor aggregation can cause crusting and cracking, decreased infiltration, increased incidences of runoff and erosion, reduced aeration and reduced drought resistance (Moebius-Clune, 2016). Through the use of best management practices (BMP), one of which is cover crops, these soil physical properties can be improved.

Cover crops offer a significant source of soil organic carbon (SOC) to agricultural soils. Just like agronomic crops, cover crops (through the processes of photosynthesis, respiration, and organic matter decomposition), add C to soils. However, cover crops do it during the time of year when annual crops are not growing. Cover crops can enhance soil quality by providing a labile source of C critical to the soils ability to control water, temperature, aeration and soil structure (Feyereisen, 2006; Hermle et al., 2008; Mazzoncini et al., 2011; Reicosky and Forcella, 1998). The amount of C that a winter cover crop can add to the soil is a function of soil type, frequency and type of cultivation, cropping residue and residue management, and fertilizer N input (Fageria et al., 2005). Non-legume cover crops increased SOC by up to 6% over a 10-yr period (Mazzoncini et al., 2011), thus improving soil quality and acting as a sink for atmospheric carbon dioxide. Cover crops can increase soil aggregation and aggregate stability largely via their C additions to soils (Liu et al., 2005). During runoff events, SOC can be transported via sediment and breakup of soil aggregates. A study from Ohio found that 44% of SOC that was mobilized through surface erosion was either lost from the field as runoff or to the atmosphere (Polyakov and Lal, 2008).

Under a long-term cereal rye cover crop study, aggregate stability increased compared to fallow (Liu et al., 2005). The seasonal variability in aggregate stability however was not affected. The use of a cover crop did not increase total soil C but instead increased the labile pools of carbon. The authors suggest that while this labile pool of C provided by the cover crop played a role in increasing aggregate stability, fungal proteins such as glomalin, also played a role in creating more stable soil aggregates (Liu et al., 2005; Steele et al., 2012). In Minnesota, a double-crop treatment of continuous corn silage and a winter rye cover crop saw a 57% improvement in the visual soil structure assessment (VSSA) compared to the control (VSSA is a tool that visually ranks the structure of the soil). The VSSA score was significant in November and June. They concluded that this rye-corn silage double cropping system added a level of protection for soil structure and physical properties (Liesch et al., 2011). In summary, cover crops are excellent anchors to hold the soil in place (reducing the erosive forces of surface runoff and raindrop impacts) while also providing soil C inputs (Kaspar et al., 2001; Langdale, 1991), building a more resilient, productive soil so they may better withstand the changing climate.

1.1.2. Impacts of Cover Crops on Soil Water Dynamics

One potential concern when using cover crops is that cover crops can use up available soil water to a point where the cash crop is negatively impacted. However, studies have shown that cover crops can also conserve soil moisture. For example, Morse (1993) found that using a cover crop as a mulch in conjunction with no-till resulted in higher soil moisture content. During the drought of 2012, soil water storage and soil volumetric water content were monitored daily for three sites in Iowa (Daigh et al., 2014). Each of these sites had a rye cover crop and a control in a corn-soybean rotation, and results showed no detrimental impact on soil water from the rye. Basche et al. (2016) analyzed continuous in-field soil water measurements from 2008 to 2014 at a central Iowa site with a winter rye cover crop grown for 13 years. They found that the cover crop used available water prior to planting but that it was replenished by rainfall back to the same soil water content as the control at the time of corn and soybean planting. This was even the case in dry years. The water holding capacity of the soil also increased under the use of cover crops due to increased residue cover, higher porosity, reduced soil bulk density, and increased aggregate stability and aggregation. These improvements in soil physical properties all play a role in improving the water storage capacity of soil. The long-term use of a cover crop increased the field capacity water content by 10-11% and increased plant available water by 21-22%. The authors concluded that the use of cover crops improved soil water dynamics. Cover crop residues left on soil improve infiltration of rain water, reduce raindrop impact force and reduce evaporative losses, resulting in less moisture stress during drought periods (Clark, 2008). Grass types of cover crops such as rye, barley, wheat and sorghum sudan grass have also been reported to be very effective at soil moisture conservation (USDA, 1998).

1.3. Nitrogen

Nitrogen loss can lead to water quality degradation, possible health risks, and a direct economic loss for farms in the form of unused N fertilizer. Nitrogen application during the growing season is often in excess to ensure an adequate supply of N to crops such as corn. This over-applied N has the potential to leach from the field. Nitrogen, specifically nitrate-N, is very mobile and its main pathway for loss is through leaching, whereas ammonium (NH_4^+) and organic N are lost in surface runoff/erosion and subsurface tile drain flow. The use of cover crops allows farmers to have a management system in place to better utilize N resources (Doran and Smith, 1991). A cover crop planted in the fall after corn silage harvest can take up excess nitrate and ammonium-N not taken up by the crop. The more time allowed for rye to grow before winter, the greater the root biomass allowing for more uptake of nitrate and ammonium-N. In a study looking at planting date and termination date in a corn-rye-soybean rotation in southwestern Minnesota, rye planted on September 15th had nearly twice as much biomass compared to planting on October 15th, 7 Mg ha^{-1} vs. 4.1 Mg ha^{-1} of dry matter, respectively. This earlier planting date also related to a greater reduction in nitrate leaching. With rye planted on September 15th and harvested as forage on May 15th, the rye was able to reduce nitrate-N leaching by 7.4 kg-

N ha^{-1}. If the rye was left until May 30th nitrate-N leaching losses were reduced on average by 11.1 kg-N ha^{-1} (Feyereisen, 2006). Another study used remote sensing to estimate rye cover crop yields and N uptake across a variety of field crops near the Chesapeake Bay in Maryland (Hively et al., 2009). The typical rotation was a corn-wheat/soybean. A total of 136 fields were used and on-farm sampling of selected fields occurred one-week after satellite imagery was obtained to calibrate the image for plant N content. Only 18% of these 136 fields were planted with a rye cover crop, the majority being in wheat. Rye had an average N uptake of 14.6 kg ha^{-1} by March 31st. Results from this study found that cover crops planted prior to the first frost (October 15th) sequestered significantly more fall N (18 kg ha^{-1}) and that a target spring biomass threshold of 1000 kg ha^{-1} resulted in greatly reduced soil nitrate-N levels (<3 mg kg^{-1}) compared to low cover crop biomass and/or bare fields (Hively et al., 2009). Another study used modeling to look at a winter wheat cover crop grown in a maize soybean rotation located in Iowa and predicted reduced N loads of 20-28% (Singer et al., 2011). In a meta-analysis of non-legume cover crops, nitrate-N leaching was reduced by an average 70% (Tonitto et al., 2006). A study in southern Michigan looked at N fertilization rates of corn (0, 101, 202 kg-N ha^{-1}) and the ability of a rye cover crop to reduce nitrate-N leaching. They found that in the heavily fertilized N fields (202 kg-N ha^{-1}), rye was able to reduce nitrate-N leaching by an average of 51 kg-N ha^{-1}, whereas lower N fertilization rates had no effect on N sequestration (Rasse et al., 2000). Therefore, in highly N fertilized fields, it is possible for rye to substantially reduce nitrate-N leaching. Based on these studies, it is necessary to establish winter rye sufficiently early in the fall for significant N uptake and reduce nitrate-N leaching risk to tile drainage and shallow groundwater. If rye biomass is left in the field as a green manure, sequestered N will be slowly mineralized and may act as a source of N for growing corn. If the goal is harvesting the rye cover crop as a hay forage crop, large amounts of N will be removed. For example, a rye dry matter yield of 2 Mg ha^{-1} with a crude protein content of 17% removes 54 kg N ha^{-1}. If rye is to be harvested, this large removal of available soil N by the rye must be compensated for the subsequent corn crop so that N does not limit yield.

1.3.1. Double Cropping with Winter Rye and Corn

Cover crops can be harvested as a hay crop forage in a management practice called double cropping. Instead of the winter cover being used for solely environmental and soil health benefits, it can also be used as forage for animals. In double cropping, nearly all above ground biomass is removed so that much less N is available to the next crop. In a Minnesota study, corn yields were negatively affected as the harvested rye resulted in a 59% decrease in soil nitrate-N, while total forage harvested (corn + rye) was similar (Krueger et al., 2011). Even though the remaining root biomass has the potential to mineralize 55% of its organic N over the course of 120 days (Malpassi et al., 2000), crops like corn will need adequate available N before this time, so fertilizer N (either applied via a starter when planting or broadcast) should be applied to make up the N deficit. By applying additional N to the corn at planting and V6 stage, it is possible to offset any yield loss from winter rye depleting soil N (Crandall et al., 2005). A meta-analysis done by Miguez and Bollero (2005), found that there was no positive or negative effect on yield for the following corn crop when using a non-legume winter cover crop. Another meta-analysis found that an application of urea at green up resulted in an average yield of 3.6 Mg ha^{-1} of dry matter for rye harvested in the flag leaf stage. With this application of urea, total dry matter production increased 17 to 51% compared to continuous corn production (Ketterings et al., 2015). In double cropping systems, planting/harvesting dates, soil N fertility, and tillage management need to be carefully managed. In general, rye biomass production is a function of seeding rate, planting date, soil fertility, and climate/geographical location. In general, late planting dates and northern locations will see decreased yields (Brennan et al., 2011). With a planting date before October 15th, which is two weeks prior to the regional average first frost date in the Chesapeake Bay region, the fall N uptake of rye was 18 kg ha^{-1} (corresponding to 1,260 kg ha^{-1} of above ground biomass). After the October 15th planting date, above ground biomass and N uptake were significantly reduced (Hively et al., 2009). A growing winter rye cover crop will take up soil N, potentially depleting soil N enough to reduce corn yield potential, however, with applications of N, this yield drag can be remedied. Applying N to the rye at green up and/or applying N at planting and V6 can offset any yield penalties associated with winter rye. When the farmer decides to apply the N depends on forage needs, management level, and soil tests.

Nitrogen is a critical nutrient for non-leguminous crops, one that is often needed as a fertilizer to achieve maximum yields. Having a cover crop growing during the off-season can potentially use up residual available N, which is good from a water quality standpoint. However, N immobilization was identified as the primary mechanism through which a cereal rye winter cover crop negatively affected corn yields (Doran and Smith, 1991). Once mineralized, N from the cover crop can be returned to the soil again and become available for plant uptake. However, mineralization rates depend on the C/N ratio of the residue, degree of incorporation, soil temperature, and soil moisture. The ideal C/N ratio for mineralization is 25:1 (Kuo, 2002). Depending on soil conditions, it may take 1 to 3 weeks after incorporation before N release exceeds N immobilization. Delaying planting by 2-3 weeks after incorporation can reduce the risk of a negative impact on corn yield from a cereal rye cover crop (Doran and Smith, 1991). Biomass is also affected by residual soil N. The more soil N available typically results in more biomass, however there is a point when biomass will fail to increase with additional N. Larger dry matter yields increase the C/N ratio, resulting in more N immobilization after termination. However, when the rate of N immobilization is matched by the N mineralization rate, rye biomass can act as a N source for the young corn (Pantoja et al., 2016). In a Washington state study, 18-25% of total N accumulated in rye biomass was in the roots (C/N ratio of 60:1) and this resulted in little to no effect on soil N availability (Kuo, 2002).

In summary, farmers interested in double cropping must understand the relative risks associated with it and have a plan to mitigate potential negative effects to the subsequent corn yield if the cover crop is harvested. In addition, a later termination date of the cereal rye prior to planting corn can also result in N depression since much of the available soil N is tied up in above and below ground biomass. Planting date of the cover crop can affect how the cover crop reacts to N use efficiency and biomass production, further complicating the balance between N immobilization and mineralization in the spring/summer. The summer crop may lack N due to it being tied up in the cover crop biomass. This potential N deficit can be offset by applying N fertilizer to the rye cover crop, especially if harvesting for forage, or by applying more N at planting and/or in season (e.g., sidedressing) to reduce risk of a yield penalty of the next crop.

1.4. Phosphorus and Erosion

1.4.1. Phosphorus and Sediment Loss

Phosphorus and sediment loss go hand in hand due to the chemical behavior of P in soils. Orthophosphate is a strongly sorbing anion readily binding to clay particles in the soil as well as Al and Fe oxides. Total P (TP) is the total amount of all P forms contained in a soil, plant, or water sample. Many factors can impact soil P sorption capacity (sorption refers to the removal of reactive P from solution through adsorption and/or precipitation reactions), such as soil type, clay content and soil pH. In low pH soils (pH<5.5), Al and Fe dissolve from mineral phases and form new minerals with P. At higher pH (pH>6.5), P tends to be bound to Ca; these Ca phosphates can leach from the soil more readily than the Al and Fe oxide-bound P. Bioavailable P, specifically $H_2PO_4^-$ and HPO_4^{2-}, are anions in solution and tend to act as weak acids. Orthophosphate ions sorb to positively charged surfaces via electrostatic forces and strongly bound to positively charged mineral surfaces through ligand exchange reactions. Phosphate can form inner-sphere bonds with two surface hydroxyl groups of the mineral surface (Strawn et al., 2015). It is P's affinity to bind to soil particles that generally make erosion the main source of P loss (Sharpley et al., 1996). Phosphorus can build up in soils through the application of animal manures and fertilizers (termed 'legacy' P), to a point where excess P can be a nonpoint source pollutant (Hart et al., 2004). Dissolved P is a combination of orthophosphate and organic/unreactive

P that can pass through a 0.45μm filter. Through the continued application of manure and fertilizers to agricultural fields, it is possible for an increase in dissolved P exports due to the soil test P reaching high levels (Sibbesen and Sharpley, 1997) and in some cases represents a significant portion of TP losses (Pierzynski et al., 2005)

1.4.2. Dissolved Phosphorus in Soil Solution and Runoff Water

Dissolved or soluble reactive P (existing as HPO_4^-, $H_2PO_4^-$, and PO_4^- depending on pH) is readily available for plant uptake, making it particularly harmful to surface waters. Dissolved P generally makes up only a small portion of TP in soil solution (Sharpley et al., 1996). Through the process of desorption and dissolution, P enters the soil solution. The amount of P desorbed to the soil solution is affected by the amount of labile P present, soil P chemistry, and the amount of contact time between flowing water and soil (Pierzynski et al., 2005). The timing of manure and fertilizer application during times of high runoff potential can also lead to dissolved P loss in runoff, particularly if manure or fertilizer are broadcast and unincorporated into the soil. Regulations in VT and NY ban the application of manure during certain parts of the year (e.g. frozen soil or water saturated soil; commonly referred to as 'winter spreading ban'). States have implemented the use of P loss risk indices to determine fields prone to P runoff, as well as require nutrient management plans that take into account soil tests and the nutrient content of the manure, to create spreading and fertilizing requirements on a field-by-field basis (Sharpley et al., 2003). In VT, a recently revised P index (Version 6.0) quantifies dissolved P loss risk in both surface runoff and tile drainage (Faulkner, 2018).

In addition to dissolved P release from soils, some studies have reported substantial dissolved P loss from cover crop biomass during freeze-thaw events. During freeze-thaw events, cell walls are damaged through cell lysis and can release ortho-P. A study by Bechman et al (2005) showed that runoff dissolved P concentrations from cover crop plots rose from 0.15 mg L^{-1} before freezing to 0.68 mg L^{-1} after freezing. A greenhouse study found that 22% of plant P was lost through leaching, 90% of which occurred in winter (Molteberg et al., 2004). In contrast, a field study in Ontario found that most of the P lost from cover crop residue (oat and red clover) during the non-growing season was taken up by the soil. The amount of P lost was a small fraction (between 2 and 10%) of total WEP (water extractable P) in the cover crop residue. However, if runoff events follow a freeze-thaw event, dissolved P losses could be larger. The authors suggest avoidance of growing cover crops in low-lying areas that experience flooding (Lozier et al., 2017). However, this is counter to what agricultural professionals and state regulations mandate, since the goal of a cover crop is to keep soil and TP on the field; Vermont requires the use of cover crops in frequently flooded soils.

1.4.3. Total Phosphorus and Total Suspended Solids

The P bound to soil and sediment enters surface waters through surface runoff and release of dissolved P, which can begin during a rain event when the incoming precipitation exceeds the infiltration rate of the soil. Rain drop impact on the bare soil can also destroy soil aggregates as well as detaching fine soil particles (Brady and Weil, 2008). These dislodged particles, many of them containing P, will then be carried with surface runoff. The rainfall intensity, slope, type of ground cover all affect soil erosion rates (Pierzynski et al., 2005). Soil erosion removes the uppermost soil layers, which typically contain larger amounts of SOC and immobile nutrients like P, the loss of which reduces crop production (Lal and Moldenhauer, 1987). A study in Wisconsin looked at TP and TSS runoff from eight agricultural watersheds (from 4-12 years of data) and showed that the largest 10% of loading events accounted for 73-97% of the TSS and 64-88% of TP. They suggest targeting BMP's to reduce exports from the largest events (Danz et al., 2013). Riparian buffer strips planted along streams can also help slow surface runoff, preventing particulate P from reaching surface waters (Dougherty et al., 2004).

Besides sound nutrient application methods such as incorporating fertilizer and manure to reduce runoff P losses, it is also important to increase infiltration and to keep the soil surface covered. Cover crops have been shown to increase surface cover, anchor soil and reduce sheet and rill erosion, leading to improved infiltration rates (Kaspar et al., 2001; Sharpley, 1991). Knowing that erosion and sediment transport can lead to environmentally detrimental P release in aquatic environments, it is critical to keep soil on the field. Relative to other BMPs, one important distinction of winter cover crops is their ability to reduce soil erosion during both the growing (assuming mulch is left on the surface/no-till planting is utilized) and non-growing season (Langdale, 1991).

1.4.4. Phosphorus Loss through Tile Drains

Historically, P losses were generally thought to occur primarily from surface runoff due to the known association between erosion, sediment transport and TP loss (Cooper and Gilliam, 1987; Sommers et al., 1979). Due to this prevailing notion, it was assumed that surface P loss would decrease through the installation of subsurface drains as the volume of surface runoff would decrease (Bengtson et al., 1995). However, in watersheds with high soil test P/low affinity to bind P and soils prone to macropore flow, significant P export can occur via tile drain flows (Baker et al., 1975). Preferential flow, which is the uneven and rapid movement of water through the soil often following wormholes, cracks, and root holes, is an important reason P can bypass the soil matrix and leach to tile drainage (King et al., 2015). Several studies have shown that dissolved and particulate P can be exported via tiles when preferential flow paths are active (King et al., 2015). No-till, which is the planting of a crop without disturbing the soil through tillage, leaves more of these preferential flow paths intact, potentially leading to significant leaching and P loss (Sims, 1998). Increases in particulate P have also been measured in tile drainage after plowing (Schelde et al., 2006), as loose soil was able to fall down macropores and bring the P-rich soil closer to tile lines. Other researchers have found that P concentrations in tile flow have been significantly reduced after tillage due to incorporation of manure or fertilizer, decreasing the likelihood of losing P to preferential flow, presumably via a combination of increased P sorption due to soil mixing and tillage breaking up macropores (Geohring et al. (2001). Through conservation tillage practices (no-till, reduced till, mulch till, strip till), it is also possible to decrease surface runoff P losses. However, subsurface losses of dissolved reactive P (DRP; considered bioavailable and readily available for plant uptake), can increase due to a greater fraction of macropores compared to a tilled system (Sharpley et al., 2001). No one method will keep P out of tiles, with the exception of long-term no-till, there are BMPs effective at reducing P loss in surface runoff and are generally recommended to reduce P loss in tile drains (e.g., soil/manure testing, nutrient budgeting, manure/fertilizer incorporation, use of cover crops, variable rate P application, improving soil health).

1.5. Research Gaps

With continued eutrophication in Lake Champlain, it is necessary to implement BMP's that limit P losses from agricultural fields. While research from the Midwest shows that winter rye can be effective at reducing N leaching in some cases, there is a lack of research in the northeast investigating water quality impacts of winter rye following corn silage. Specifically, there is little research in the northeast US quantifying how much sediment, P, and N can be reduced in surface and subsurface runoff by a winter rye cover crop. In addition, there is a lack of information on potential impacts of rye cover crops on corn silage yield and whether it is practical to consider harvesting rye as a forage crop. With the current economic hardships on many dairy farms, it is important to keep costs down and determine how winter rye can be integrated into crop rotations without negatively impacting corn yields.

1.6. Objectives and Hypothesis

The objectives of this study were to: 1) quantify differences in surface and subsurface runoff water and nutrient losses between corn silage plots with or without a rye cover crop over two growing seasons at research farm in northeast Clinton County, NY and 2) estimate winter rye yields and determine if corn silage yields are affected by growing a rye cover crop. Specific hypotheses were:

- Sediment and runoff nutrient losses (N and P) will be lower for the rye cover crop treatment
- Surface runoff volumes will be lower for rye cover crop treatment
- Total forage biomass harvested will be greater for rye cover crop treatment

Chapter 2 : Materials and Methods

2.1. Site Description

The Lake Alice Wildlife Area in Chazy, NY (44˚52'30.49"N; 73˚28'51.08"W) is home to many waterfowl and four research plots. These four plots are in a 1.65 ha field that until 2012 was managed as a cool season grass *(Phalaris arundiancea)*, with no crop rotations, one cutting a year, and no known manure history. Clinton County receives an average of 80 cm yr^{-1} of precipitation and has an average growing season of 130 days.

The four plots (Figure 1) established in this 1.65 ha field are 45.7 m long by 22.9 m wide with plot lengths oriented up and down to the relatively uniform hill slope of 5%. The transverse slope across the plots is <1%. Field observations indicated no mixing of surface runoff flows across plot boundaries for a range of hydrologic events. The four plots transition from excessively drained outwash soil (Colosse-Trout River complex; *sandy-skeletal, mixed, frigid Entic Haplorthods*) on the upslope to a poorly drained silty clay series at the toe slope (Adjidaumo; *fine, mixed, active, nonacid, frigid Mollic Endoaquepts*) (Trevail, 2006). Soil samples were taken from the upper three horizons in the center of each of the four plots and sent to the University of Maine Soil Testing Service for agronomic testing following Cornell University soil testing methods (Morgan soil test extractant). The depths of each horizon across all four plots were: Ap horizon 0-30cm, Bw horizon: 30-51cm, and the B/C horizon: 51-91cm. The B/C horizon extended beyond 91cm, the pits were only excavated to the 91cm depth.

In the fall of 2013, the grass sod was terminated with an application of glyphosate. Composted dairy manure was broadcast applied at 15 Mg ha^{-1} followed by primary tillage with a disk harrow. Corn silage (Zea mays L.) was planted in June 2014 at 84,000 seeds ha^{-1}. At planting, 168 kg ha^{-1} of 23-12-18 dry fertilizer was placed in a in a band 5 cm below the seed and 5 cm to the side through the planter. Corn silage was harvested in fall of 2014, followed by another application of liquid dairy manure (15 Mg ha^{-1}) that was not incorporated due to an early snow storm. All plots were left fallow over the winter of 2014-2015. Corn silage was again planted in the spring of 2015 with the same fertilizer application and seeding rate.

2.2. Experimental Design

In 2012, the four plots were modified to collect subsurface and surface runoff from each plot individually (Figure 1). Each plot received three artificial subsurface drainage tile lines, which were installed parallel to the field slope and centered in each plot. Tile lines were installed at approximately 1 m below the soil surface. These tile lines drained to a 15 cm PVC pipe that connected to individual concrete manholes, where subsurface and surface runoff waters were sampled and flows measured.

Surface runoff collection trenches were installed using 30 cm PVC pipe that was cut in half and installed in shallow gravel lined trenches at the base of each plot. Trenches had a slight grade to allow drainage via gravity to the manholes. Metal flashing and gravel, 1m wide, was placed on the field side of the trenches to stabilize the soil, this gravel was at field grade. The gravel did not collect any sediment during the duration of the study. Construction of surface trenches was completed in the summer of 2013.

The previous study had two of the tile outlets blocked (plots 1 and 3) from installation to the fall of 2015 (Klaiber, 2016). Until that point, management was identical. On

October 9th, 2015 the two plugs were pulled on the tile lines from plots 1 and 3 and all plots subsequently had free flowing tile drains. Approximately 11 Mg ha^{-1} of composted dairy manure was applied in early October followed by incorporation using a disk harrow. Based on manure nutrient content, this provided 13.7 kg-TP $ha^{-1}$and 47.7 kg-TN ha^{-1}.

The four plots were blocked (block 1 = plots 1 and 2; block 2 = plots 3 and 4), and the rye cover crop treatments were randomly assigned and plots 1 and 3 were selected to receive the rye treatment. On October 7th, 2015 winter rye (*Secale cereale*) was drilled into plots 1 and 3 at a rate of 112 kg ha^{-1}. On May 23rd, 2016 corn was planted into the standing rye (Figure 2) at a rate of 84,000 seeds ha^{-1}, a starter of 168 kg ha^{-1} of 23-12-18 dry fertilizer was also applied at this time. On May 24th, 2016 the rye was terminated with glyphosate. On September 19th, 2016 the corn silage was harvested. In the three weeks between harvest and planting of the rye, approximately 11 Mg ha^{-1} of composted dairy manure was applied and incorporated using a disk harrow. Based on manure N and P, approximately 13.7 kg-TP $ha^{-1}$and 47.7 kg-TN ha^{-1} were applied. On October 11th, 2016 winter rye was planted using a grain drill (112 kg ha^{-1} in plots 1 and 3). On May 30th the winter rye was sprayed with urea and ammonium nitrate-N UAN, 70 kg-N ha^{-1}. On June 7th, 2017 the winter rye was mowed using a Pottinger Nova Cat 356F mower and on June 8th, 2017 it was chopped for haylage. This was followed by a light incorporation using a disk harrow. On June 15th corn silage was planted at 84,000 seeds ha^{-1}, a starter of 168 kg ha^{-1} of 23-12-18 dry fertilizer was also applied at this time. Corn silage was harvested on October 11th, 2017 concluding the study.

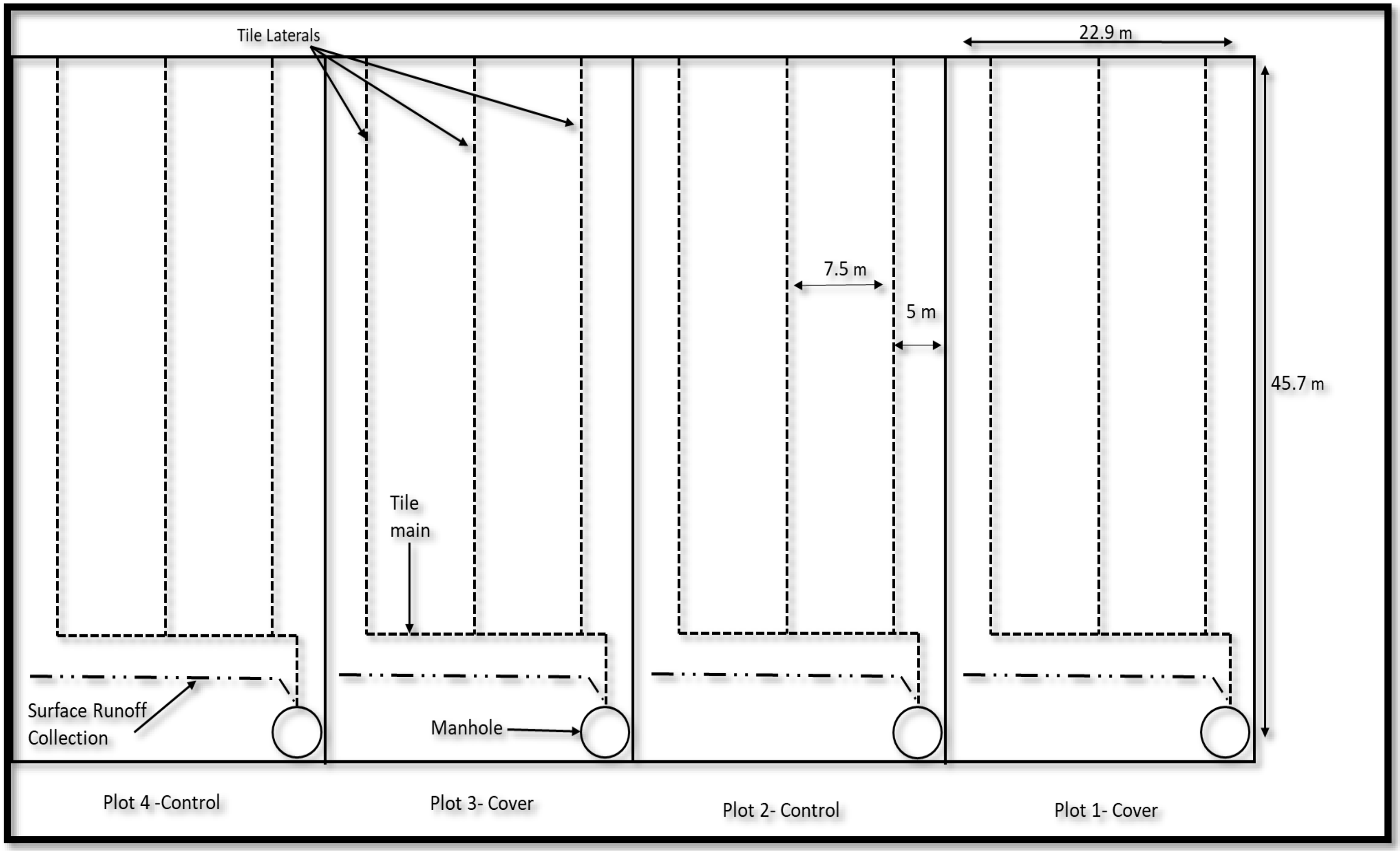


Figure 1. Plot layout at the Lake Alice Wildlife Area, Chazy, NY. Three tile laterals centered and spaced at 7.5m apart and approximately 1m deep were installed in 2012. These drained to a tile main which emptied into a manhole installed in the lower right corner of every plot. Surface water was collected via a 12-inch PVC pipe cut in half and placed in a shallow gravel lined trench at the base of the plots. Each manhole housed two five gallon buckets modified with v-notch weirs and pressure transducers. Plots were blocked, block 1= Plots 1 and 2; block 2= Plots 3 and 4, cover crop treatment was randomly assigned to plots 1 and 3.

Figure 2. Planting corn into standing rye on May, 23rd 2016 using a John Deere 1750 6 row corn planter at 75-cm row spacing.

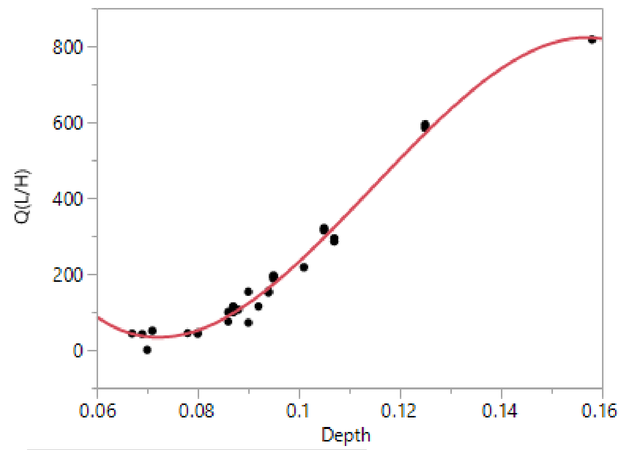
2.3. Water Flow Measurements

Inside of each manhole were two, five gallon buckets to quantify, surface and sub-surface runoff flows from each plot. These five-gallon buckets were modified with v-notch weirs to enable stage-discharge relationships to be determined (Figure 3). Each bucket was equipped with a 5-cm PVC stilling well in which a HOBO U20 Water Level Logger (Onset Computer Corporation, Bourne, MA) was housed to determine water levels. There was an additional logger in the manhole of plot 4 that recorded barometric pressure, (to transform logger pressure readings to water depth using the HOBO software). Loggers were programmed to record a measurement every 5 minutes.

Runoff flows were quantified with small v-notch weirs made from five-gallon plastic buckets. Six of the eight buckets were designed and used in a previous study (Klaiber, 2016) and two additional buckets were constructed for the present study. The previous study showed strong curvilinear relationships between water height in buckets and measured flow rates in the laboratory and field. Equations from (Klaiber, 2016) were used for 4 of the 6 buckets. For the two new buckets, grab samples were taken at various flows (using a time to fill a known volume to estimate instantaneous discharge). Cubic regression models were fit to field measured flows (Figure 4) using JMP PRO 11.2 (SAS Institute., Cary, NC) and used to predict water runoff flows. Both field and laboratory data points were combined for the tile buckets to provide a more robust regression model. Some predicted flows showed a slight increase at very low water levels (0.08m); this level was close to the minimum detectable flow and flows below this level were considered to be zero.

During the winter months snow accumulated on the plots. Prior to a major snow-melt events snow water equivalent (SWE) measurements were performed on each plot based on the methods outlined by Sturm et al. (2010) . Three samples were taken per plot and SWE was calculated from the average. SWE for each plot was then converted into a volumetric runoff equivalent (mm) to be able to compare it to the rain events.

Figure 3. Inside the manhole. The top bucket collects the surface runoff while the bottom bucket is for tile flow. The gray PVC pipes housed the HOBO data loggers. Photo on the right depicts the v-notch weir with active surface runoff.



Summary of Fit

RSquare	0.981927
RSquare Adj	0.980749
Root Mean Square Error	20.98325
Mean of Response	159.8986
Observations (or Sum Wgts)	50

Figure 4. Rating curve developed for plot 1 and 3 tile flow buckets, Flow (L/h)= 704.5755+9786.0136*Depth+82281.22*$(\text{Depth}-0.09458)^2$-1360109.5*$(\text{Depth}-0.09458)^3$. Regression was created with JMP using a combination of field and lab measurements (n=50). The tail upwards at the bottom of the curve was ignored since the minimum possible water depth was 0.08m.

2.4. Water Sampling and Nutrient Measurements

Samples were collected from the PVC outlets in each manhole during runoff events. During short duration events (lasting < than 12 hours), 1-3 grab samples were taken. An attempt was made to capture the rising limb, the peak, and the falling limb of runoff hydrographs. For longer duration rain and snowmelt events, ISCO 6712 automated samplers (Teledune ISCO, Lincoln, NE), hereafter referred to autosamplers, were deployed. Autosamplers were set to take a 200 mL sample every 30 minutes, compositing this sample with 4 others, each sample bottle represented two hours' worth of runoff. For some extended events where the tiles were still influenced from the event, sample bottles were composited into 6 hour blocks using a flow weighted mean. Grab samples were immediately transferred back to Miner Institute, at the completion of the sampling cycle autosampler bottles were than brought back and refrigerated. For some longer duration events (> 24 hours), samples were collected prior to the 24 hr mark and new sample bottles were placed in the autosampler while the first samples were brought back and refrigerated.

Soluble reactive P (SRP) was determined within 48 hours of collection after filtering through a 0.45 µm membrane filter by the ascorbic acid-ammonium molybdate colorimetric method (Murphy and Riley, 1962; APHA, 1989) using a spectrophotometer (Thermo Fisher Scientific Inc., Waltham, MA US). Total P (TP) and total N (TN) were determined after digestion following the Standard Methods 4500-N/P (APHA, 1989). Nitrate-N, (which will be abbreviated NO_3 for simplicity) was analyzed using a SEAL AutoAnalyzer AA3 continuous segmented flow analyzer (Seal Analytical, UK), as per method 4500-NO_3 from APHA (1989). Total suspended solids (TSS) were run on every sample using Proweigh filters (Environmental Express, Charleston, SC) per Standard Methods 2540 (APHA, 1989).

2.5. Water Yield and Load Calculations

The HOBO water level loggers were downloaded every 2 to 4 weeks and depth readings converted into flow for each plot/runoff pathway (Table 1). Each v-notch weir bucket had its own minimum flow value (water level) that would result in measurable flow and was determined by filling each bucket to the bottom of the v-notch and then averaging multiple subsequent readings. This water height was used to remove points where there was no flow since some equations produced flow values at readings <0. After this was completed, the 5 min flow rates were summed to mean hourly flows. Water yields from each plot were expressed as a volumetric runoff depth (mm) by dividing the total water runoff volume by plot area. In events where autosamplers were deployed, flow means associated with the sample taken by the autosampler were multiplied by the flow during that time period to obtain loading estimates (e.g., kg ha^{-1}). For tile drain flow autosampler events, samples bottles (3 bottles) were grouped into 6-hour sections. An aliquot from each bottle in the group was taken and placed in a new bottle with aliquots based on the percentage of flow that occurred within the 6 hrs. To calculate the load estimates for grab samples, hourly mean flows were summed and multiplied by the concentrations of SRP, TP, nitrate-N, TN, and TSS. If an event had more than one grab sample, concentrations were assumed to be the constant from the halfway point between the two samples. These concentrations were than multiplied by the corresponding hourly mean flows to calculate loads (King et al., 2015a). Total loads were calculated from each treatment on an event and cumulative basis for the study duration.

Most runoff events were captured during 2016-2017, however some runoff events that occurred in the winter months were unable to be quantified due to water freezing and ice buildup on flow buckets. In winter and early spring 2016, there was also an issue with the manholes not draining and flooding to the point where the v-notch weirs were submerged. The cause was found to be tree roots in the drainage of the manholes and was fixed later in the spring of 2016.

Table 1. Rating curve for each runoff collection location, where y= flow (L/h), x= water depth (m), RMSE= root mean square error, and n=number of observations. Rating curve equations for surface buckets and tile buckets from plots 2 and 4 were created by previous study. Buckets for tile buckets from plots 1 and 3 was created for this study using lab and field measurements. Buckets were identical and had the highest R^2 when data points were combined.

Source	Rating Curve Equation	R^2	RMSE	n
Plot 1 Surface Flow	$Y = -1253.784 + 12814.592x + 259905.13*(x-0.11437)^2 + 2092942.2*(x-0.11437)^3$	0.99	60.4	38
Plot 2 Surface Flow	$Y = -1179.754 + 13110.917x + 188035.1*(x-0.10615)^2 + 2618310.9*(x-0.10615)^3$	0.98	261.3	40
Plot 3 Surface Flow	$Y = -977.8281 + 10684.031x + 258932.18*(x-0.10245)^2 + 2368245.2*(x-0.10245)^3$	0.92	52.9	58
Plot 4 Surface Flow	$Y = -774.6562 + 7816.3228x + 186538.03*(x-0.11068)^2 + 1179312.4*(x-0.11068)^3$	0.98	58.7	19
Plot 1 and 3 Tile Flow	$Y= -737.3717 + 9586.9931x + 58787.93*(x-0.09082)^2 - 2196110.2*(x-0.09082)^3$	0.97	23.4	50
Plot 2 Tile Flow	$Y = -1114.649 + 10826.456x + 308017.64*(x-0.11358)^2 + 2200297.4*(x-0.11358)^3$	0.99	30.7	65
Plot 4 Tile Flow	$Y = -888.0222 + 10038.702x + 231885.28*(x-0.10525)^2 + 5207383.1*(x-0.10525)^3$	0.98	34.3	65

2.6. Pre-Sidedress Soil Nitrate Test

Plant-available soil N was estimated by the pre-sidedress nitrate test (PSNT). A composite sample from each plot was taken every 1 to 2 weeks from June 2016 to June 2017, except when frozen or excessively wet soils prohibited sampling. The objective was to determine if mineralization of rye biomass occurred. Six soil samples were taken from each plot, composited, then dried for two days in a 55˚C oven. The difference between wet and dry soil mass was used to estimate gravimetric water content. Samples were sieved to 2 mm and 5 g was placed in a 125 mL Erlenmeyer flask with 125 mL of 2 *M* KCL, samples were run in duplicate (Magdoff, 1991). Flasks were placed on a reciprocating shaker for 15 min after which they were gravity filtered through a Whatman filter number 4. The filtrate was than analyzed on a SEAL AutoAnalyzer AA3 as per Standard Methods 4500-NO3 (Federation, 1989) for nitrate-N concentration, expressed as mg-NO_3-N kg^{-1} of dry soil.

2.7. Rye Harvest

The winter rye was sampled weekly in 2016 and 2017 over the course of 4 weeks prior to harvesting to ascertain how quality and yield change over time. Rye sampling started the just prior to flag leaf stage and finished when rye was at the boot stage (Table 2). Each rye plot (plots 1 and 3) was broken into 4 quadrants and a sample was randomly taken from each quadrant, giving 4 samples total. A sampling frame with a known area (20 x 100 cm) was used, cutting height was at 10 cm to simulate a typical mowing height used when harvesting winter grains as a hay crop.

The biomass was collected, weighed, and subsamples were dried for dry matter content determination and nutrient analysis. Rye biomass yield was calculated by using frame size dimensions and scaling up the average dry matter yield an area of 1 ha. Dried and ground samples were sent to Dairy One (Ithaca, NY) for analysis of crude protein content, acid detergent fiber, neutral detergent fiber, undigested fiber (at 30-hr time point) and P content.

Table 2. Winter rye harvest dates for both years of the study.

	Sample 1	Sample 2	Sample 3	Sample 4
2016	5/10/2016	5/17/2016	5/22/2016	*
2017	5/18/2017	5/23/2017	6/1/2017	6/7/2017

*Winter rye in 2016 reached boot stage after 3 weeks. 2017 weather lead to a slower growth.

2.8. Corn Silage Harvest

Corn silage was harvested using a John Deere 3975 two-row corn forage harvester with a 30A Plot Harvest Sampler from RCI Engineering (RCI Engineering LLC, Mayville, WI) equipped with digital on-board load cells. Each plot was divided into three subplots. Plots were chopped, weighed, and subsampled using the built-in diffuser within the 30A unit. Plot yields were calculated from the mean of subsample weights. Subsamples were weighed, dried and ground to 1mm using a Wiley Mill. Corn forage samples were dried and ground samples were sent to Dairy One (Ithaca, NY) for analysis of crude protein content, acid detergent fiber, neutral detergent fiber, undigested fiber (at 30-hr time point) and P content.

2.9. Statistical Analysis

Runoff plots were arranged in a randomized complete block design. Cover crop treatments were randomly assigned to plots within each block. The plots lay across a north to south transect and blocked with respect to their position (the two southernmost plots (1 and 2) and the two northernmost plots (3 and 4) were designated as the two blocks). Cubic regression models were constructed for each 5-gallon bucket, using a combination of lab and field data points. Response variables measured included SRP, TP, nitrate-N, TN, TSS, runoff water yields, rye/corn biomass yield. Pearson correlation coefficients were used to quantify linear relationships between TSS, TN, and TP using JMP Pro 12 (SAS Institute Inc., Cary, NC TSS and TP/TN. Mean response was tested for differences by event (n=16) and for cumulative totals using a student t-test. Mean differences were also tested for PSNT values (n=17), as well as rye (n=4) and corn biomass (n=8). All statistical analyses was performed using JMP pro 12 (SAS Institute Inc., Cary, NC). Significance was declared at a p-value ≤ 0.05 and trends at a p-value ≤ 0.10.

Chapter 3 : Results and Discussion

3.1. Surface Runoff and Tile Drainage

A total of 16 runoff events were analyzed over the study period; 13 were rain events and 3 were snowmelt events. Rainfall events contributed a cumulative total of 336.0 mm of water to plots while snowmelt events contributed 299.4 mm of (SWE) (Table 3). Both summers were relatively dry and several rainfall events produced no flow. For 12 out of 19 months rainfall was below average for Clinton County (Figure 5). Across treatments, mean plot volumetric runoff equivalent (surface runoff + tile flow) for rainfall events had 87.5 mm of runoff compared to 151.4 mm for runoff from the snowmelt. Snowmelt events generated 64% of the total event runoff and was consistent with a study from Vermont that found increased watershed runoff from snowmelt events compared to rainfall events (Shanley and Chalmers, 1999). A study from Ontario found that 65% of the total water came from snowmelt events (Cuelly, 1993), and was attributed to more water available for runoff as well as frozen soils that limited infiltration to subsurface drainage. Cumulative total runoff water yield (surface + tile) was significantly lower for rye plots compared to the control (Figure 6). Cumulative surface and tile runoff volumetric depth for rye was 198.4 mm (±17.5) compared to 279.7 mm (±26.6) for control. Winter rye reduced surface runoff by 31%. A winter wheat cover crop in the Midwest reduced surface runoff by 62% (Sharpley et al., 2001). Cover crops can also slow surface water runoff velocity up to 5-fold compared to bare soil (Dabney, 1998), allowing more time for surface water infiltration. Brill and Neal (1950) found a winter rye cover crop increased infiltration throughout the year. A cover crop with sufficient biomass (>2000 kg ha^{-1}) will transpire between 50 and 60 mm of water (Meisinger et al., 1991), leading to increased infiltration for subsequent rain events (Dabney, 1998), further reducing risk of surface runoff. In a simulated rainfall study from Iowa, winter wheat reduced surface runoff by 10% (Kaspar et al., 2001). The results from these studies support the findings here, indicating significantly reduced surface runoff potential from rye compared to corn left bare after harvest (Figure 8).

In the spring of 2017 there was a series of snowmelt and rainfall events that produced large runoff volumes (Table 4). The first event was a snowmelt that occurred from February 20-24th, followed by a rain event on the 25th. There was nearly a month of no runoff before the next snowmelt event on March 25th. This was followed by two rainfall events on the 2nd and 6th of April. From the SWE and calculated runoff values (surface + tile), the amount of runoff retained (%) was estimated for each plot (which is essentially the water that fell on the plots but not measured in runoff). For these five events (two of which were snowmelt), rye plots had greater apparent water retention that could reflect a greater ability to capture and store runoff water. Studies suggest that a cover crop can increase available storage water capacity (Dabney, 1998; Meisinger et al., 1991) in addition to increasing infiltration from more soil macroporosity. Reduction of surface sealing can also result in up to 5-fold slower surface runoff velocities (Dabney, 1998; Tomlin et al., 1995). The last event (4/5/2017) showed almost no water retained and could be related to: i) high antecedent soil water content and relatively low ET rates at this time of the year, ii) initiation of soil thawing allowing greater infiltration, iii) high water table and groundwater flow overwhelming possible water retention by rye biomass. The 2017 snowmelt events highlight seasonal changes in soil water as the soils thawed as well as the ability of rye to potentially increase the soil water storage capacity.

Surface runoff and tile flow from select events in the spring of 2017 show a decrease in surface runoff from rye plots and an increase in tile flows (Figure 9, 10, 11, and 12). Surface runoff from rye plots took longer to reach peak flows compared to control, particularly for the 3/27/17 snowmelt (Figure 9). For this event (3/27/17), runoff from rye plots and control plots both started around the same time, however runoff from rye plots increased sharply at 5pm on the 27th, whereas runoff from rye plots increased steadily to the first peak for both treatments at 4pm on the 28th. It is possible that the rye biomass slowed surface runoff, which is reflected in the hydrograph (Figure 9), since runoff velocity can be reduced by using a cover crop (Dabney, 1998). Increased resistance to flowing water has not only reduced runoff velocities, it results in less erosive forces (e.g. less erosion/production of rill erosion) as well as reducing peak flows to streams reducing bank erosion (Kuhnle et al., 1996). For the events with tile flow (2/25/17, 3/27/17, 4/7/16), runoffs were similar, however flow from rye plots tended to be greater (Figure 8), possibly indicating greater rates of infiltration (Dabney, 1998; Kaspar et al., 2001; Tomlin et al., 1995). Higher tile flows in plot 1 may also be partially attributed to its low relative elevation and more ground water inputs compared to other plots. While it is possible rye increased infiltration and flow to tiles, other research has reported that a rye cover crop reduced tile runoff by 21% due to greater transpiration as well as increased soil water storage capacity (Qi and Helmers, 2010). The increase of decrease in tile flow depends on management, soil type, and local weather patterns.

Table 3. Total rainfall that fell on each plot or was in the snowpack (mm) for each sampled event and the total for sampled events. Snowmelt events marked with an *. Event date, start time, end time and total rainfall are listed for each event. The event on 4.2.17 did not have SWE measured.

Event Date	Event Start	Event End	Rainfall/ Snowpack (mm)
3.28.16	3.28.16 4:00	3.29.16 4:00	18.3
4.7.16	4.7.16 5:00	4.8.16 10:00	29.0
4.11.16	4.11.16 8:00	4.12.16 12:00	10.4
6.5.16	6.5.16 9:00	6.5.16 11:00	37.3
6.28.16	6.28.16 14:00	6.28.16 11:00	20.6
7.9.16	7.9.16 4:00	7.9.16 21:00	21.3
7.18.16	7.18.16 11:00	7.18.16 11:00	18.3
8.14.16	8.13.16 3:00	8.14.16 3:00	28.4
8.28.16	8.28.16 2:00	8.29.16 2:00	35.3
10.21.16	10.21.16 6:00	10.23.16 9:00	44.2
2.20.17 *	2.20.17 14:00	2.24.17 23:00	131.4*
`2.25.17	2.25.17 16:00	2.25.17 11:00	30.2
3.27.17 *	3.27.17 0:00	3.30.17 22:00	168*
4.2.17*	4.2.17 8:00	4.2.17 22:00	10.4 + Snowmelt
4.6.17	4.6.17 11:00	4.7.17 4:00	18.5
6.29.17	6.29.17 12:00	6.30.17 4:00	24.1
Total Event Rainfall			336.0
Total Event Snowmelt (SWE)			299.4
Total Rainfall and Snowmelt			634.8

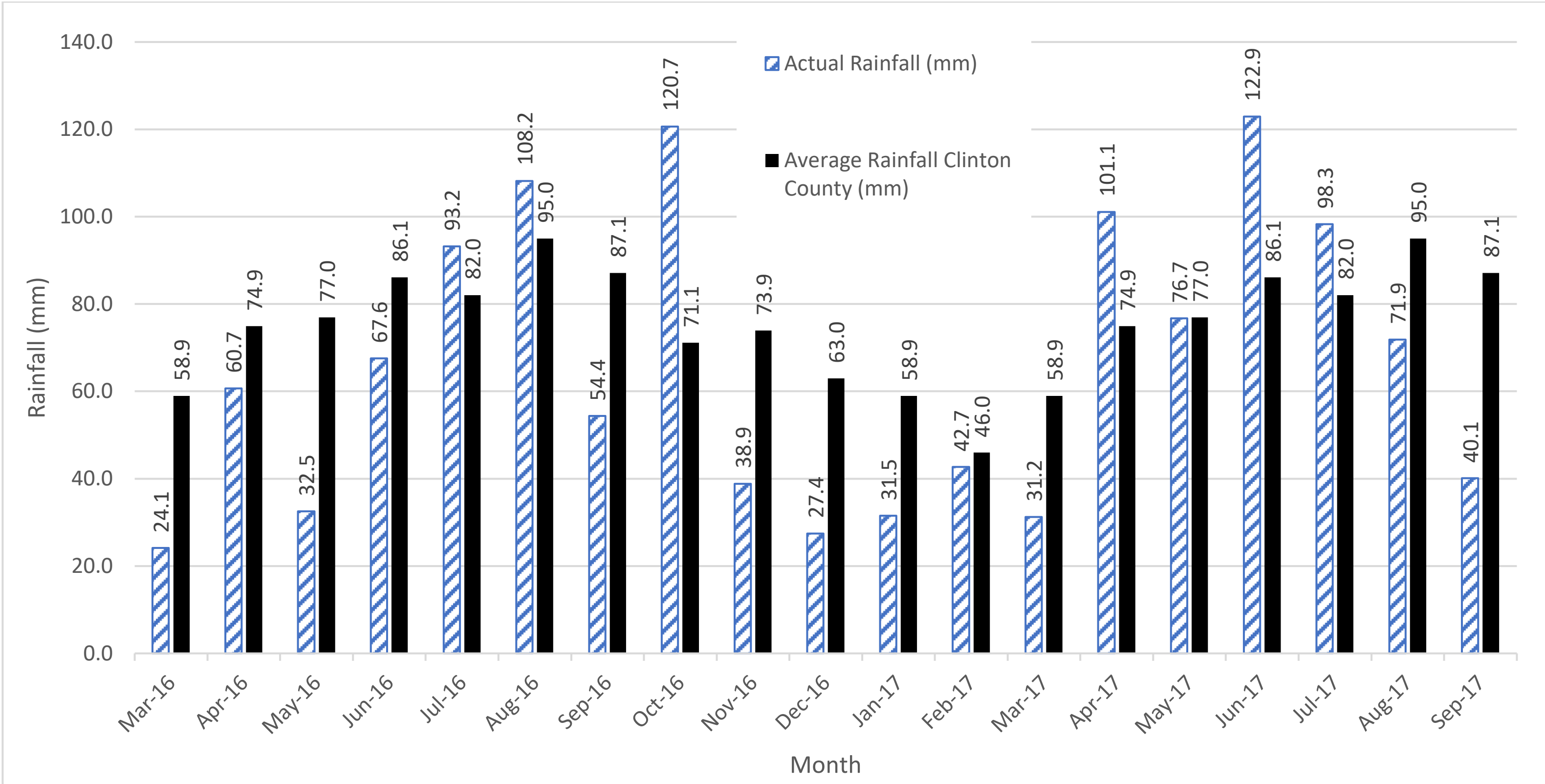


Figure 5: Monthly precipitation at Miner Institute and Clinton County, NY average rainfalls for study duration. Note 12 out of 19 months had lower than average rainfall.

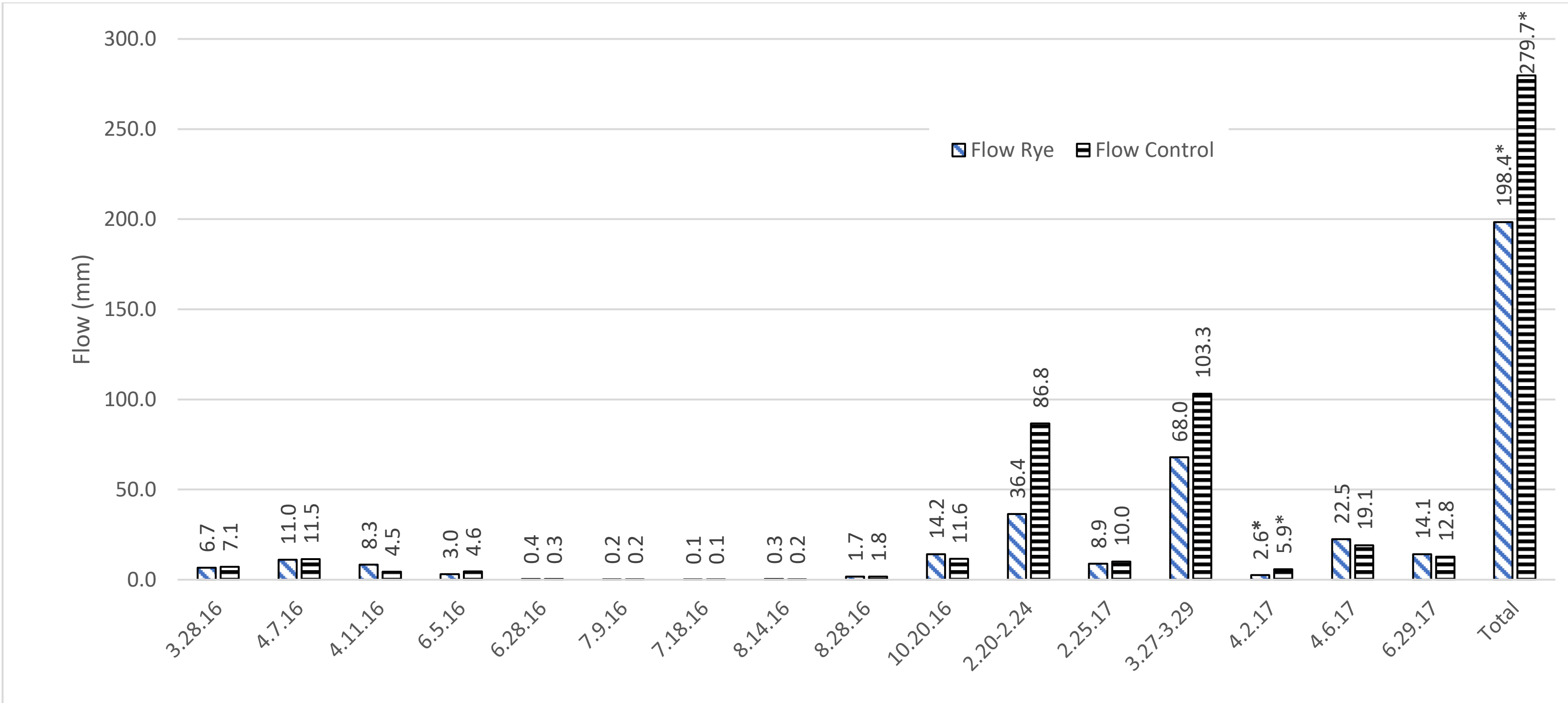


Figure 6. Mean total runoff water yield for surface and tile by treatment for individual events and study total. Values with an * denote a significant difference (*p*≤ 0.05) between cover and control treatments. A value with ** indicates mean values were trending towards significance (*p*≤ 0.10).

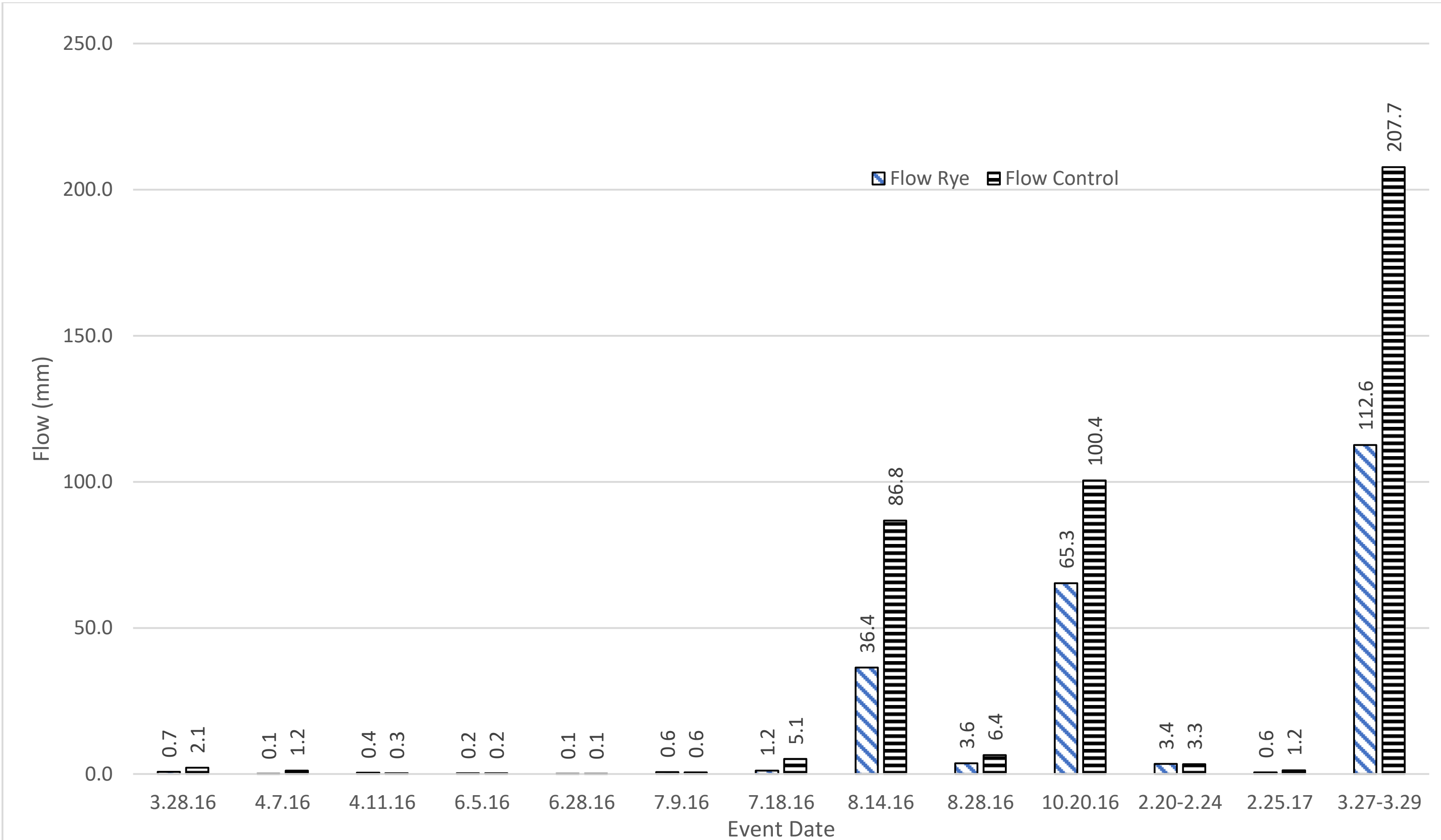


Figure 7. Mean surface runoff by treatment for the 16 sampled events. Values with an * denote a significant difference ($p \leq 0.05$) between cover and control treatments. A value with ** indicates mean values were trending towards significance ($p \leq 0.10$).

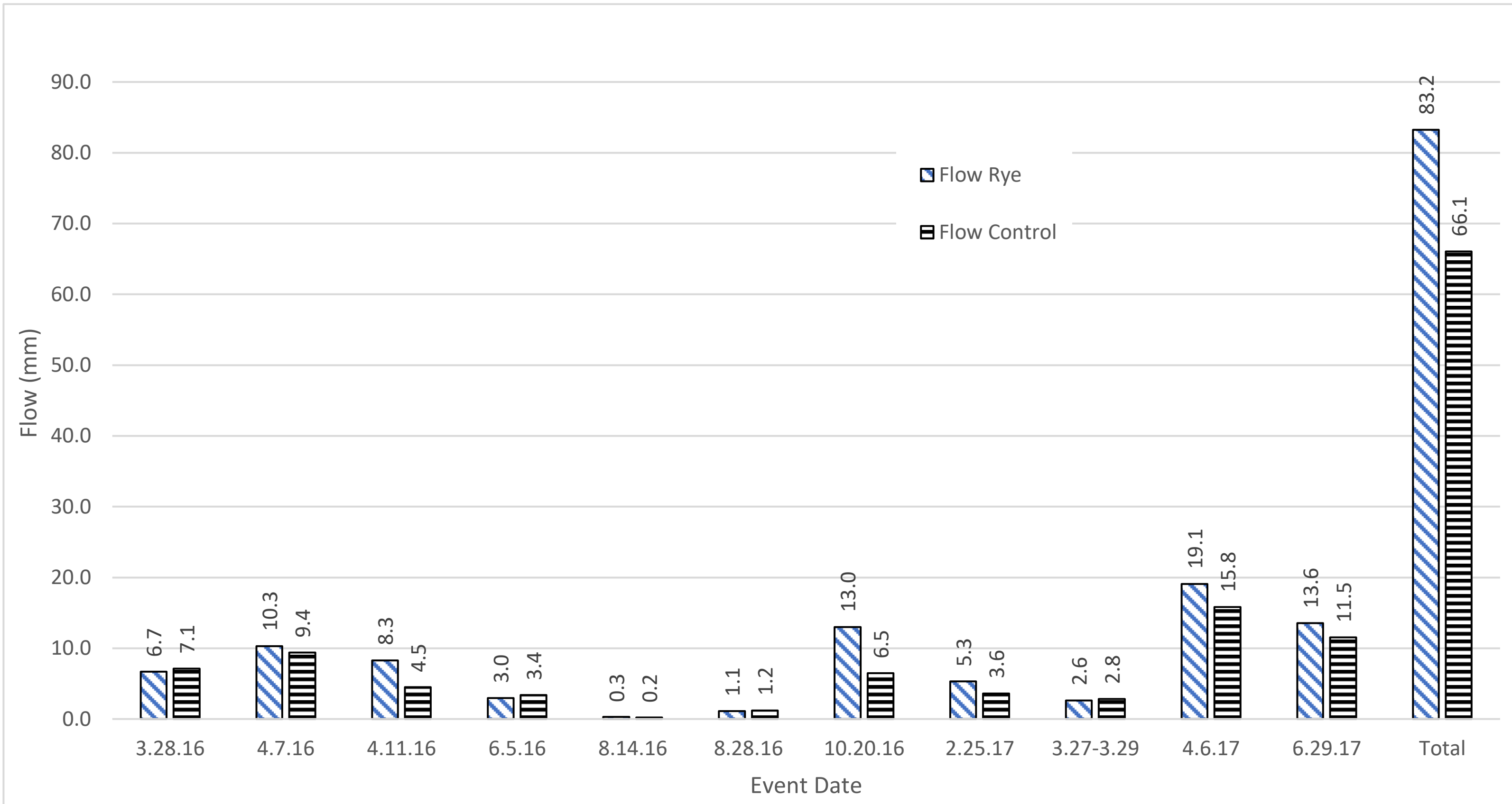


Figure 8. Mean tile drain runoff flows by treatment for study duration. Values with an * denote a significant difference (*p*≤ 0.05) between cover and control treatments. A value with ** indicates mean values were trending towards significance (*p*≤ 0.10).

Table 4. Selected events in spring of 2017, snowmelts and rainfall events by treatment flow path and apparent amount of water recovered.

Event Date	SWE (mm)	Rainfall (mm)	Surface run-off Cover (mm)	Surface runoff Control (mm)	Tile flow Cover (mm)	Tile flow Control (mm)	% Recovery (Cover/Control)
2.20.17-2.24.17 Snow-melt	131	-	37	88.4	6.9	5.67	67/30
2.25.17 Rainfall	-	24.5	3.6	6.4	5.3	3.6	64/60
3.25.17 Snowmelt	170	-	65.4	100.4	2.6	2.8	60/40
4.2.16 Rainfall	-	10.4	2.6	5.9	0.0	0.0	75/44
4.6.17 Rainfall	-	21.4	3.4	3.3	19.1	15.8	0/10

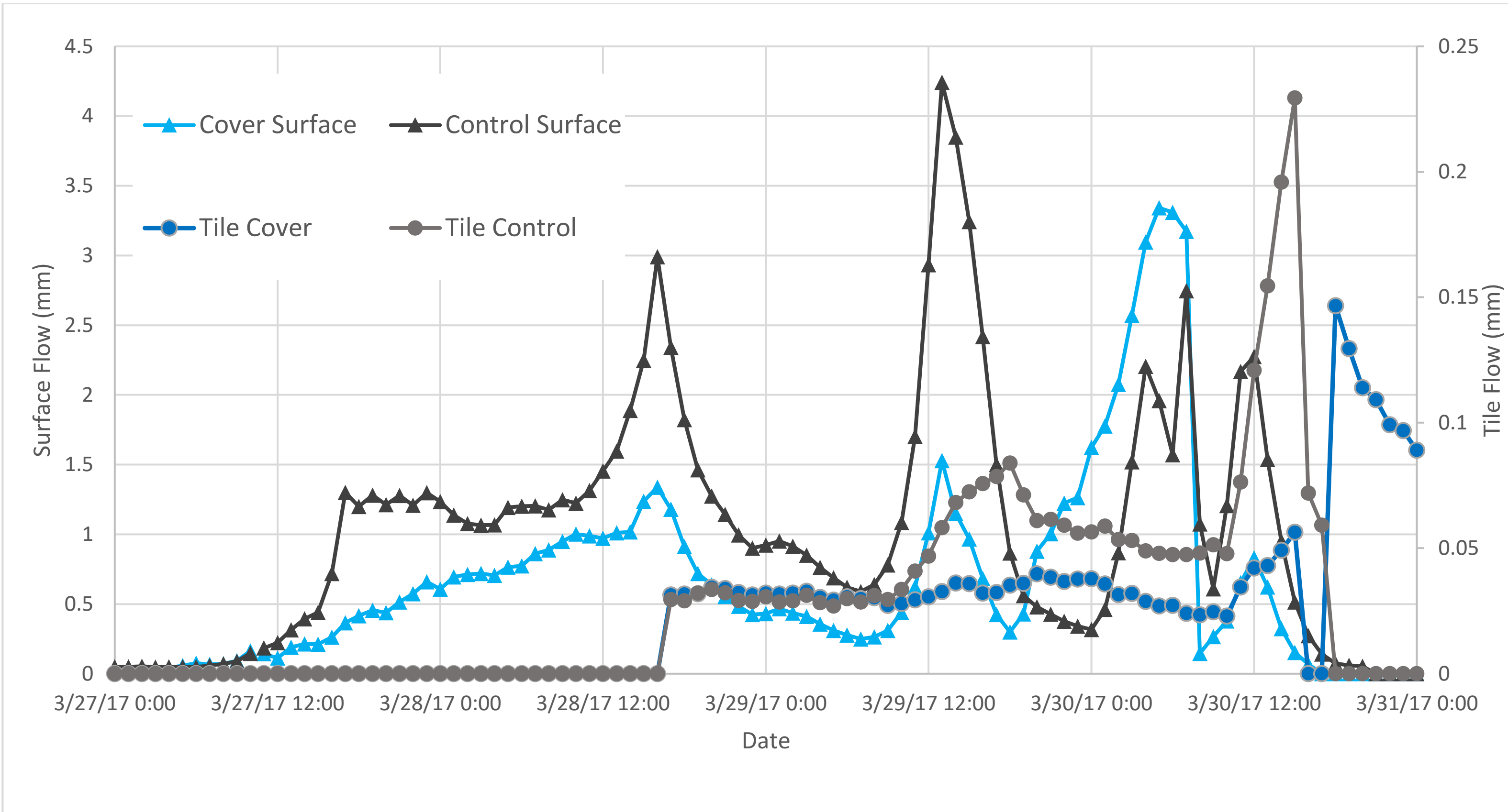


Figure 9. Surface and tile drain runoff flows for the 3.27.17 snowmelt event for rye and cover treatments.

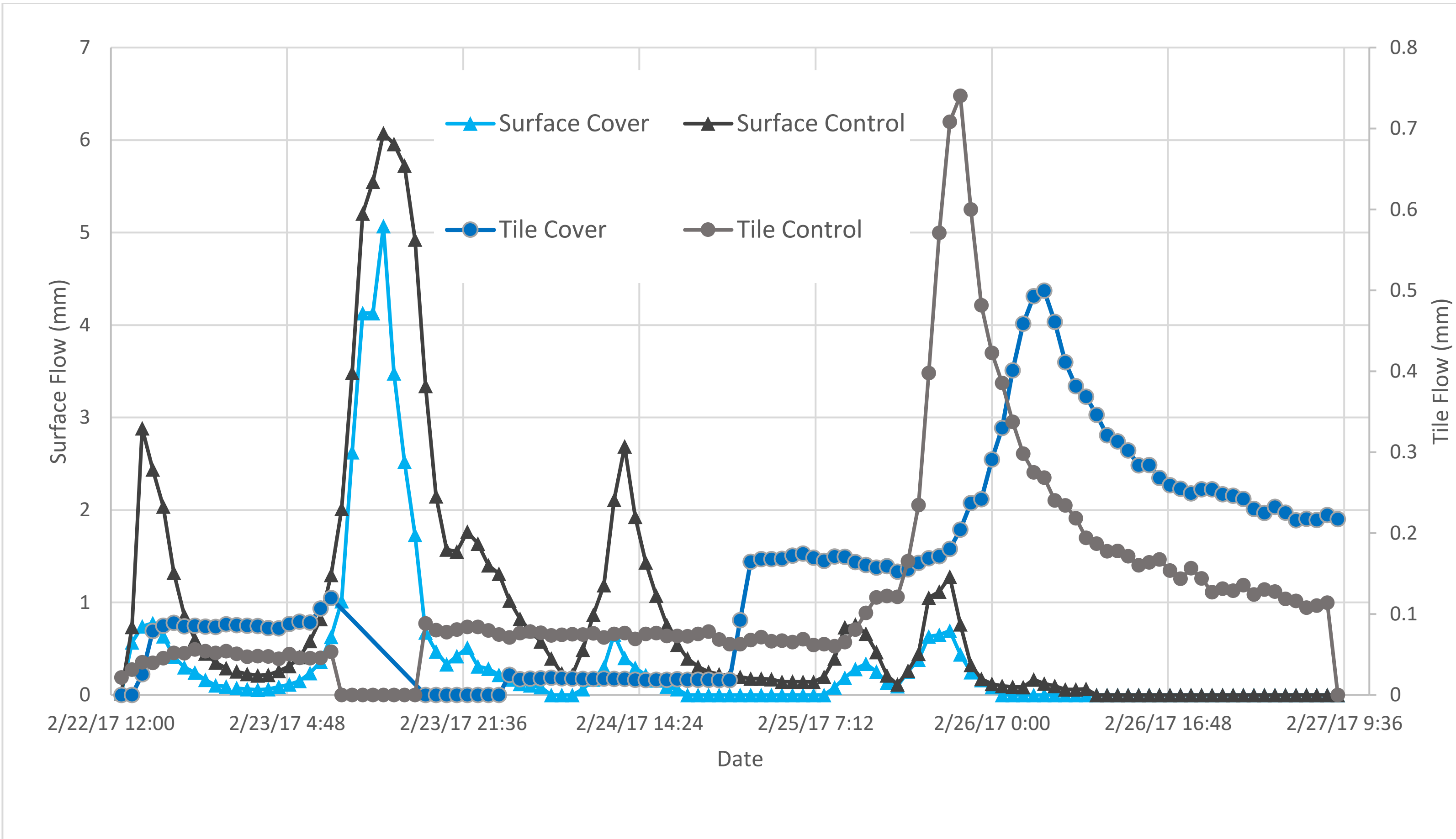


Figure 10. Surface and tile drain runoff flows for the 2/22/17 snowmelt event for rye and cover treatments.

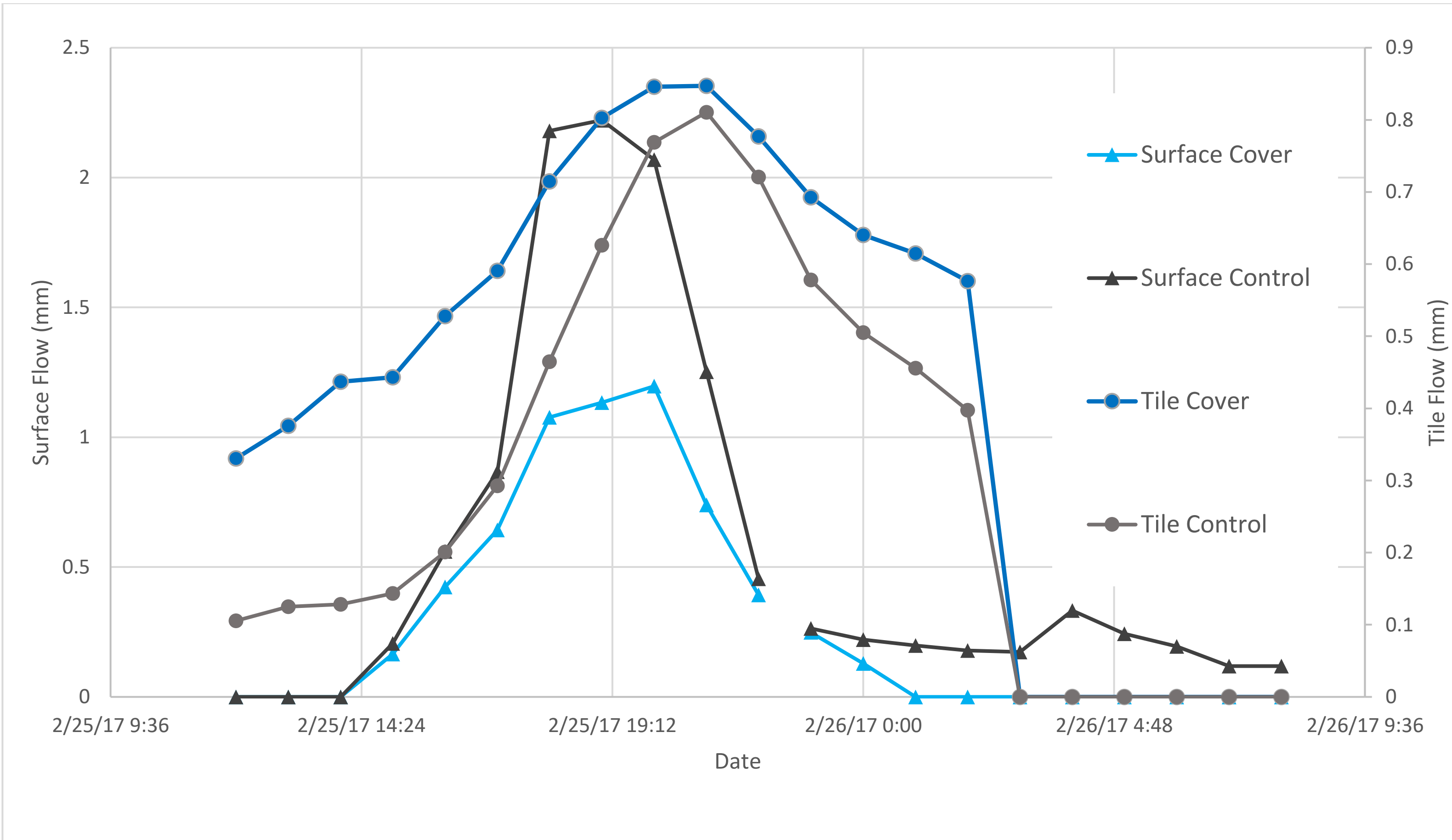


Figure 11. Surface and tile drain runoff flows for the 2/25/17 rainfall event for rye and cover treatments.

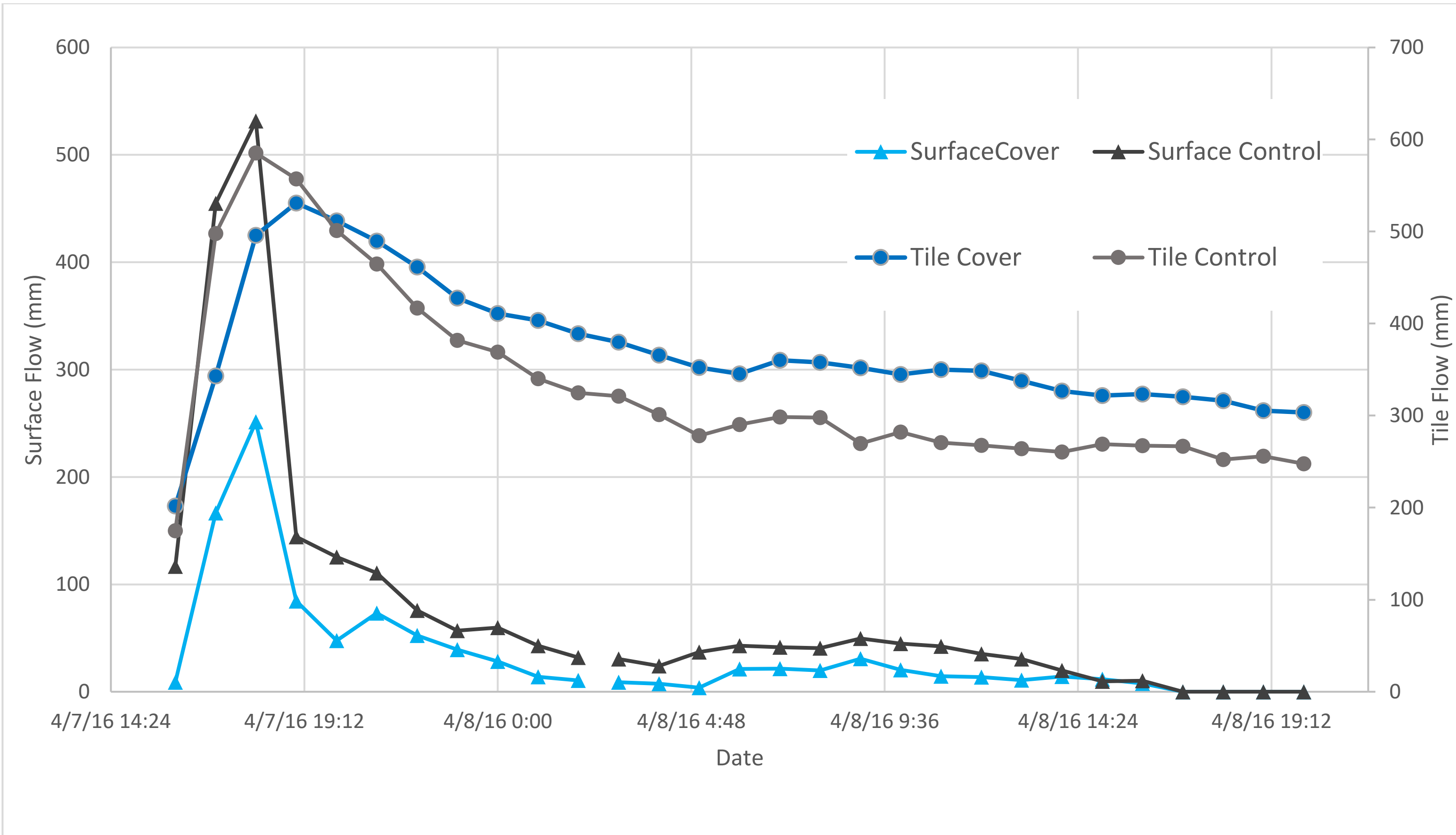


Figure 12. Surface and tile drain runoff flows for the 4/7/17 rainfall event for rye and cover treatments.

3.2. Total Runoff Water Yields

Over the course of the study, 1351.7 mm of rain and SWE fell on the plots, generating 757.3 mm (±233.9) of tile runoff for rye and 441.7 mm (±181.1) for control. While these were not significantly different, they represent large differences with respect to field soil water budgets. Rye plots produced 124.7 mm (±94.7) of cumulative surface runoff while control had 269.1 mm (±169.1) (Table 5), representing a 53% reduction in surface runoff by rye plots for the study duration. A study from the southern plains found a winter wheat cover crop reduced surface runoff by 62% (Sharpley, 1991). Infiltration was not directly measured in the present study; however results suggest rye may have contributed to greater overall water infiltration/lower surface runoff compared to bare soil conditions. This is consistent with Kaspar et al. (2001) who found that winter wheat increased infiltration rates by 16% while reducing surface runoff by 10%. This is consistent with Dabney (1998), who suggested three different ways a winter cover crop can increase infiltration: i) preventing surface sealing/crusting, ii) increasing soil water storage, and iii) increasing soil macroporosity.

During the winter of 2017, there were times when buckets froze and manholes backed up with water (generally for <24 hours). During these times, only rough flow estimates were possible based on readings preceding the freezing/flooding, resulting in a large underestimation of runoff. As previously mentioned, it is hypothesized that plot 1 may have been influenced by groundwater more than others. Plot 1 occupies the lowest landscape position and the seasonally high-water table is closest to the soil surface as evidenced by redoximorphic features present at shallower profile depths. Tile drain flow for plot 1 was often prolonged during events relative to other plots and had the highest average flow over the study compared to other plots (Table 6). Plots were not hydrologically isolated, so we cannot be certain that the flow from tile 1 was not influenced from adjacent plots or deeper groundwater flow paths.

Table 5. Treatment mean water yields for each flow path for the study duration. Bold values denote a significant difference ($p \leq 0.05$) in mean values between rye and control treatments.

Total	**mm**	**SD**
Rainfall + Snow-melt	1351.7	-
Tile Cover (mm)	757.3	233.9
Tile Control (mm)	441.7	181.1
Surface Cover (mm)	**124.7**	94.7
Surface Control (mm)	**269.1**	169.1

Table 6. Flow averages for each runoff pathway for the duration of the two-year study. S represents surface flow path and T represents tile flow path. Flows are in mm.

Plot	Flow (mm)
1S	10.4
2S	14.4
3S	2.8
4S	6.8
1T	9.5
2T	5.7
3T	4.4
4T	5.4

3.3. Soil Phosphorus and Pre-Sidedress Nitrogen Testing

An agronomic soil test was taken at the start and end of the study (Table 7). At the beginning of the study, all plots had low soil test P (approximately 1 mg kg^{-1}). After two-years, soil test P values increased in 3 of 4 plots (plot 2 remained at 1 mg kg^{-1}). Composted dairy manure was applied each fall at a rate that applied approximately 27 kg-TP ha^{-1}. Plot 1 had the largest soil test P increase (from 1 to 4 mg kg^{-1}), while plots 3 and 4 increased to 2.5 and 1.5 mg kg^{-1}. There was an average increase in STP of 125% across all plots. The larger increase for plot 1 could be due to in part to uneven application of manure. Despite attempts to apply manure evenly, heavier application was apparent in portions of plot 1. At the end of the study, rye plots had a tendency ($p = 0.01$) for higher soil test P.

Soil organic matter (SOM) at the start of the study ranged from 28 to 35 g kg^{-1}. At the end of the study, all plots had numerically greater SOM relative to initial levels. The increase in SOM may be partially attributed to rye biomass and application of dairy manure. Mean SOM for rye plots was 43 g kg^{-1} while control plots had a mean of 33 g kg^{-1} ($p = 0.27$). With more continuous use of rye as a cover crop, more consistent and sustained increases in SOM may be possible over time. Over the course of a 10-year study, SOM significantly increased due to the use of cover crops, using conventional tillage, and no-till (Mazzoncini et al., 2011).

Pre-sidedress soil nitrate tests (PSNT) were attempted to be taken weekly over the course of the two summers (Figure 13), however due to the nature of N in the soil, if plots were excessively wet, samples were not taken. The results were inconclusive among treatments as there was high variability among plots and across sampling dates. The sampling dates in 2016 may have reflected some mineralization of rye biomass since it was left as a green manure. However, since both treatments were elevated through June and July, other factors influencing nitrate availability including manure application variation and heterogeneity in soil properties affecting mineralization and denitrification (soil water content, oxygen status, labile organic carbon availability). It is also worth noting that all PSNT results were <21 mg kg^{-1} threshold set by Cornell, indicating additional N is required for maximum yield (Ketterings Quirine M. et al., 2012). The soil nitrate spike in October may have been related to the application of composted dairy manure a few weeks prior (applying 48 kg-N ha^{-1}, mainly as organic N). A greenhouse study in Iowa looking at rye root mineralization rates found that control pots stopped mineralizing N after 60 days where as the pots with rye roots continued to mineralize N until the end of the study which was 120 days, however there was no application of N to the rye during growth or after harvest, which resulted in the rye pots being lower in soil N (Malpassi et al., 2000). This might have also been the case in our study, especially since in 2016 the rye did not receive any N. The difference being in our study the entire plant was left to mineralize. We did measure higher soil N levels than Malpassi et al. (2000).

Table 7. Results from soil tests taken at the start and end of the study. The 2015 soil sample was taken 12/18/15. The 2017 soil sample was taken 3/11/17. Six soil samples from each plot were taken and mixed together to get a representative sample for each plot.

	2015				2017			
	1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Phosphorus (mg kg^{-1})	1	1	1	1	4	1	2.5	1.5
Potassium (mg kg^{-1})	81	73	73.5	123.5	176	129.5	171	148
Calcium (mg kg^{-1})	1219.5	1398.5	1465.5	915.5	1095	1515.5	1814	1493.5
Magnesium (mg kg^{-1})	244	278	261	123	201.5	258.5	241.5	160
pH)	5.9	6.31	6.5	5.9	6	6.5	6.6	6.4
Iron (mg kg^{-1})	7.85	4.75	3.15	4.9	6.55	4.4	3.25	3.8
Manganese (mg kg^{-1})	10.65	10.25	10.5	8	13.3	12.1	17.75	12.7
Zinc (mg kg^{-1})	0.85	0.9	0.7	0.6	0.85	0.55	0.9	0.6
Aluminum (mg kg^{-1})	37.35	33.65	23.05	48.4	34.2	33.05	23.2	31.9
Organic Matter (g kg^{-1})	33	33	35	28	39	36	44	34

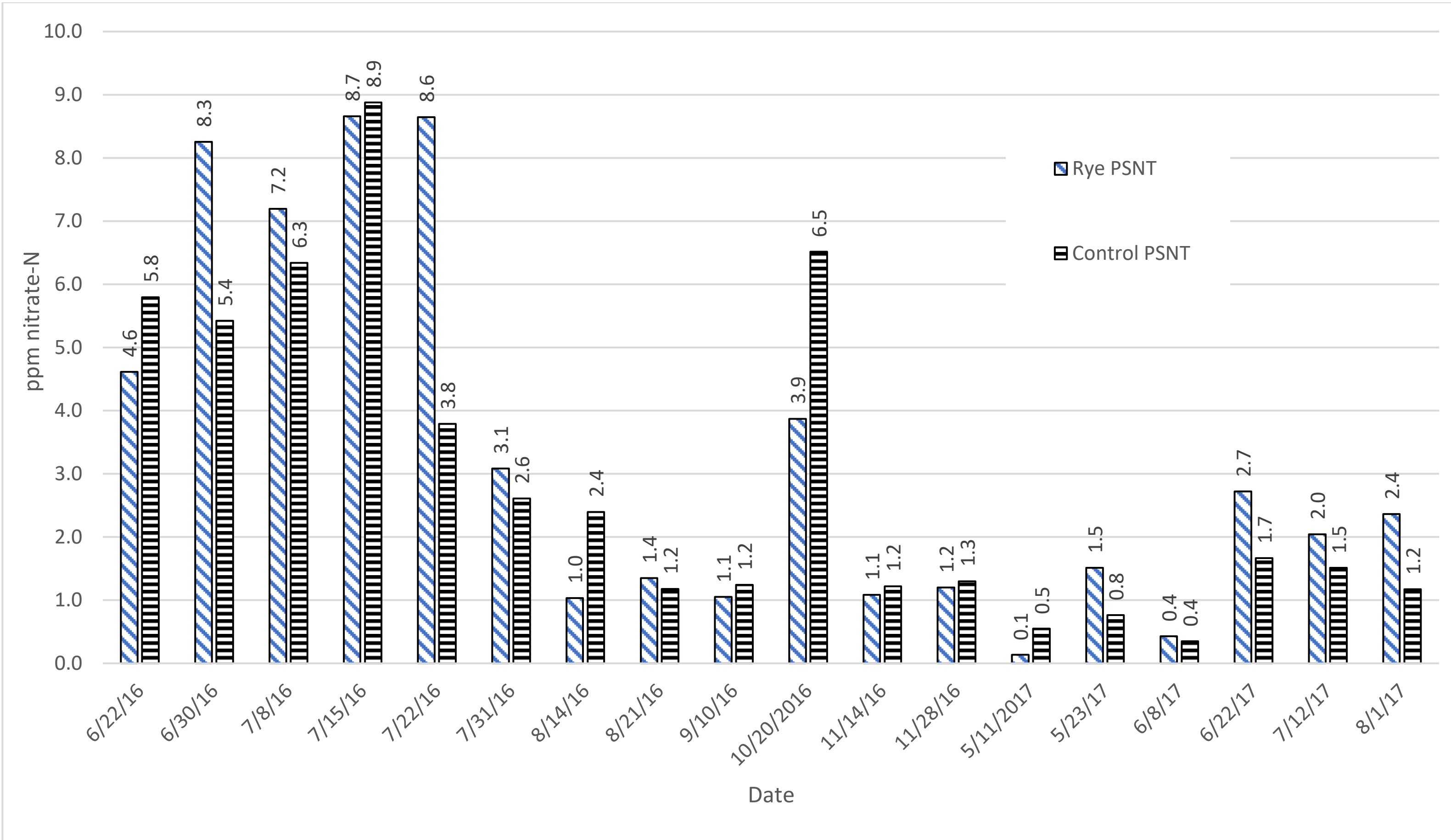


Figure 13. PSNT results for soil samples taken from each treatment over the course of the study when conditions permitted, n=18.

3.4. Phosphorus and TSS losses

Phosphorus loads for each treatment were calculated for all 16 events as well as total export over the study duration (Figure 14) for surface runoff and tile drainage pathways (Figure 15 and 16). Total SRP export for the study duration was significantly lower for rye (335 ±49 g-P ha^{-1}) compared to the control (9634 ±144 g-P ha^{-1}). Total P export was also significantly lower for rye plots (510 ±59 g-P ha^{-1}vs. 1197 ±166 g-P $ha^{-1}$for control; Figure 14). Surface SRP losses for the study duration were significantly lower for rye (316 ±64 g-P ha^{-1}) compared to corn plots without rye (944 ±192 g-P ha^{-1}). Surface TP losses were also significantly lower for rye plots (364 ±69 g-P ha^{-1}) compared to corn plots without rye (1128 ±220 g-P ha^{-1}). There was more variability in tile losses, with no significant differences in SRP or TP losses between treatments.

There were no significant differences in TSS loads between treatments on an event basis, however TSS losses were numerically higher for control plots. This is similar to what was found in analysis of runoff samples across New York State, which was attributed to variability in runoff volumes obscuring differences in suspended solids (Kleinman et al., 2005). Rye plots lost 14.4 ±1.3 kg TSS ha^{-1} while the control treatment lost 26.5 ±2.7 kg ha^{-1} for total export (surface + tile; Figure 17). Surface losses for TSS were (5.7 ±0.7 kg ha^{-1}) for the rye plots and (20.6 ±3.5 kg ha^{-1}) for the control (Figure 18). A study in Iowa found that a winter wheat cover crop reduced interrill erosion by 62% (Kaspar et al., 2001). Tile TSS losses were greater in rye plots, this possibly related to the previous study, where tile outlet drains in plots 1 and 3 were plugged to simulate undrained conditions and its impact on P export (Klaiber, 2016). Since flow was stopped, sediment, particularly fine clays, were able to settle out and accumulate in tile laterals. During some events (more often in 2016), sediment was mobilized and flowed out of the tile. Tile water from these two plots also had visual discoloration compared to control plots, potentially due to finer particles remaining in solution. Filters clogged rapidly for these samples, further indicating higher concentrations of particulate and/or colloidal matter. Cumulative mean tile TSS load was 2.7-fold greater for rye plots compared to control (8 ±2 kg ha^{-1} for rye plots vs. 3 ±1 kg ha^{-1} for control; Figure 19). In addition, two events had significantly higher tile drain TSS loading from rye plots (plots 1 and 3), suggesting the blocking of tile flow for the previous study likely increased both TSS and P export from tiles drains in the rye plots. It is also possible that the presence of rye was able to effectively increase infiltration (Kaspar et al., 2001), perhaps leading to greater macropore flow and possibly greater risk of TSS and P transport to tile flows.

There were significant correlations between surface TP losses and TSS losses for both rye and control (r= 0.81 $p \leq 0.001$ and r= 0.38 p=0.05, for cover and control, respectively; Figure 20). There was a slightly higher correlation with TP and TSS in control plots, which could be due to more sediment mobilization from those plots. It is also possible that TSS from cover plots contained less sediment-bound P and more rye residue. Using the numerical difference between TP and SRP as an estimate of unreactive/bound/particulate, for rye plots to control we found that there was 3.9 times more unreactive/bound/particulate P (URP) leaving from surface runoff in the control treatment. The URP losses and TSS losses for surface runoff were significantly correlated (r=0.68 $p \leq 0.001$; for both treatments, Figure 21). There was also a highly significant correlation between TP and TSS export in tile drainage across all events for both rye (r= 0.95; $p\leq0.001$) and control (r= 0.97; $p\leq0.001$) respectively (Figure 22), suggesting P was being mobilized through the tile system with particulate matter in both treatments. Further evidence of this increased P mobilization in tile drains is the rye treatment had 2.7 times more URP. The URP losses and TSS losses for tile runoff were significantly correlated (r=0.96 $p\leq0.001$; for both treatments, Figure 23). The increase of URP seen in rye plots tile drainage could be from the artifact from the previous study and/or the increased infiltration and macropore water flow associated with rye biomass in combination with the no-till planting that occurred in 2016.

For all of the events, 97% of cumulative SRP export came from surface runoff and 87% of TP exported came from surface runoff. A study from Quebec on sandy clay loam and loam soils found 60% of cumulative SRP and TP losses came from surface runoff (Jamieson et al., 2003). A Minnesota study on silty clay soils found 97% of SRP and 99% of TP came from surface runoff under a moldboard plowing treatment, whereas 75% of SRP and 79% of TP left through surface runoff in a reduced tillage management system (Zhao et al., 2001).

Given that that the majority of P losses were through surface runoff, it is essential to lower P losses through this pathway. The winter rye cover crop significantly reduced surface SRP and TP losses by 66.6% (Table 8). A meta-analysis from the mid-west found a winter cover-crop reduced SRP and TP losses between 70% and 75% from surface runoff (Sharpley, 1991), supporting findings here. Given this significant reduction in P losses from surface runoff and since the vast majority of P came from surface runoff, the rye cover crop effectively reduced P losses and was as an important management practice for reducing potential negative water quality impacts.

Over the course of the two-year study, there were 13 events that produced surface runoff and were sampled intensively. Of these 13 events, 3 were snowmelt events. These occurred in the winter and spring of 2017. These snowmelt events generated 96% of the SRP and 92% of the TP that was lost over the course of the study for surface runoff. This was driven in part by the increased runoff from these events; 65% of the total surface runoff was generated by these snowmelt events. A study from eastern Canada found that snowmelt losses dominated SRP and TP export in agricultural watersheds (Su et al., 2010). Another study from Quebec found that snowmelt events accounted for 99% of SRP and 96% of TP export over two years. Only 4 runoff events occurred during this study with the one snowmelt event accounting for 99% of cumulative runoff for the study (Jamieson et al., 2003). In the present study, three snowmelt events accounted for >90% of TP and SRP export over the two years, however, rye plots reduced SRP and TP export by approximately 3-fold. This reduction in P export during snowmelt events is similar in magnitude to reductions for rainfall events, where rye reduced SRP and TP export by 3.5- and 3.6-fold, respectively (Table 9). This slightly higher reduction for rain events could be due to higher TSS transport and more effective sediment trapping of rye during the non-winter period. A watershed study in Wisconsin reported that the majority of TP in snowmelt was in dissolved form (Danz et al., 2013), which support findings here. While dissolved P can be difficult to control with a cover crop alone, results indicate that rye was effective at reducing P loss during the growing and non-growing season. Results stress the importance of sound nutrient management (e.g., manure incorporation, use of cover crops, soil P testing) that can help mitigate P transport during both rain and snowmelt driven runoff events.

Assessing SRP and TP ratios in snowmelt and rainfall events revealed a difference between the two types of events. For simplicity, two snowmelt events and two rainfall events in the spring of 2017 were selected to contrast. In the snow melt events (Figure 24, Figure 25), the dominant form of P lost was SRP, accounting for >90% of TP loss. In the rainfall events (Figure 26, Figure 27), SRP accounted for <50% of the TP. The differences in P fractions lost in the snowmelt and rainfall events could be due to the rainfall events being more erosive compared to melting of the snow. The snowmelt events also had a longer duration, lasting a couple days compared to the rain events that were <1 day; this increased event duration may have also contributed to greater P release compared to rain events. Additionally, dissolved P may be more mobile under colder soil conditions compared to warmer soils during the growing season (Williams et al., 2011; 2012). A study in Minnesota looking at P losses during winter snowmelt found that 75% of cumulative P export was SRP regardless of tillage type (Hansen et al., 2000). Dissolved P is of particular concern to surface waters as it is readily bioavailable and once waters warm can lead to toxic algae blooms as P and algae increase proportionally (Schindler et al., 2008).

Based on findings here and the literature, winter rye is an important practice for reducing surface runoff P losses in corn silage systems. The majority of P losses come from surface runoff losses and the majority of surface P losses came from snowmelt events. In order to increase the likelihood of successful winter rye establishment and associated surface runoff water quality benefits, planting should be done prior to October 15th for sufficient biomass growth going into winter. Do to winter rye's ability to anchor soil and reduce runoff/increase infiltration, planting rye on steep to moderately sloped fields after corn silage has the potential to reduce erosion and P transport risk.

Table 8. Cumulative P loss from surface runoff and tile drainage and P (%) reduction in surface runoff from rye cover crop. Rye significantly reduced cumulative surface runoff TP and SRP losses (*p*≤0.001 over the study duration.

	SRP (g-P ha^{-1})	TP (g-P ha^{-1})
Surface total	1260	1491
Tile Total	58	244
% From Surface	96	86
% Phosphorus reduction in surface runoff from rye treatment	66	66

Table 9. Surface P losses from rainfall and snowmelt events. The reduction of P by using a winter rye cover crop was calculated by dividing the loss from the control by the loss from the rye. The last two rows are the % of P from the whole study that was generated in snowmelt and rainfall events.

	SRP (g-P/ha)	TP (g-P/ha)
Total Cover	316	364
Total Control	944	1128
Cover Rainfall	11	26
Control Rainfall	38	93
Cover Snowmelt	307	338
Control Snowmelt	906	1034
Reduction Rainfall	3.5 fold	3.6 fold
Reduction Snowmelt	3.0 fold	3.1 fold
% P generated from snowmelt	96.1	92.0
% P generated from rainfall	3.9	8.0

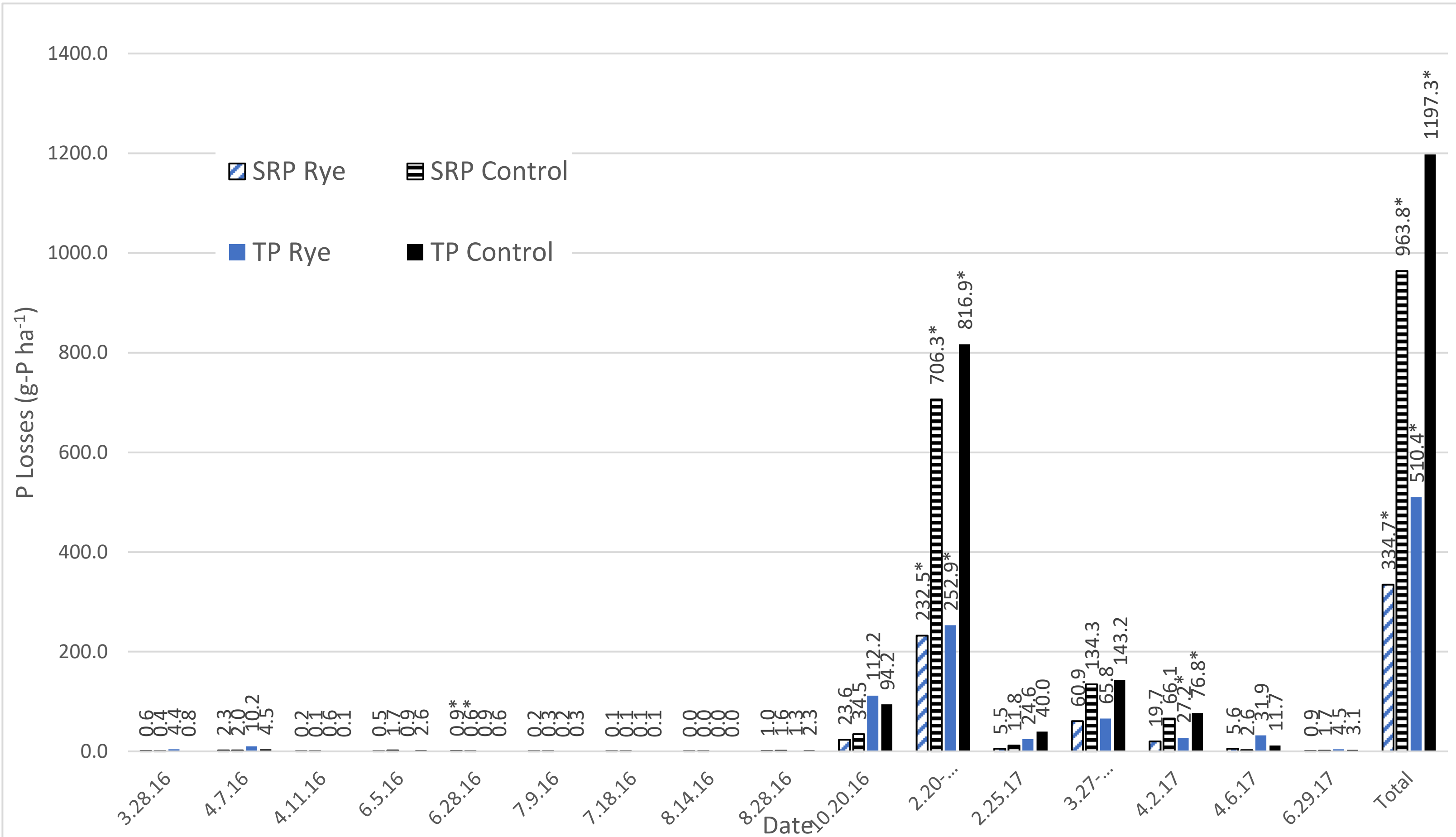


Figure 14. Combined surface and tile phosphorus losses (TP and SRP) for every sampled event over the course of the study. Values with an * denote a significant difference ($p \leq 0.05$) between cover and control treatments. A value with ** indicates mean values were trending towards significance ($p \leq 0.10$).

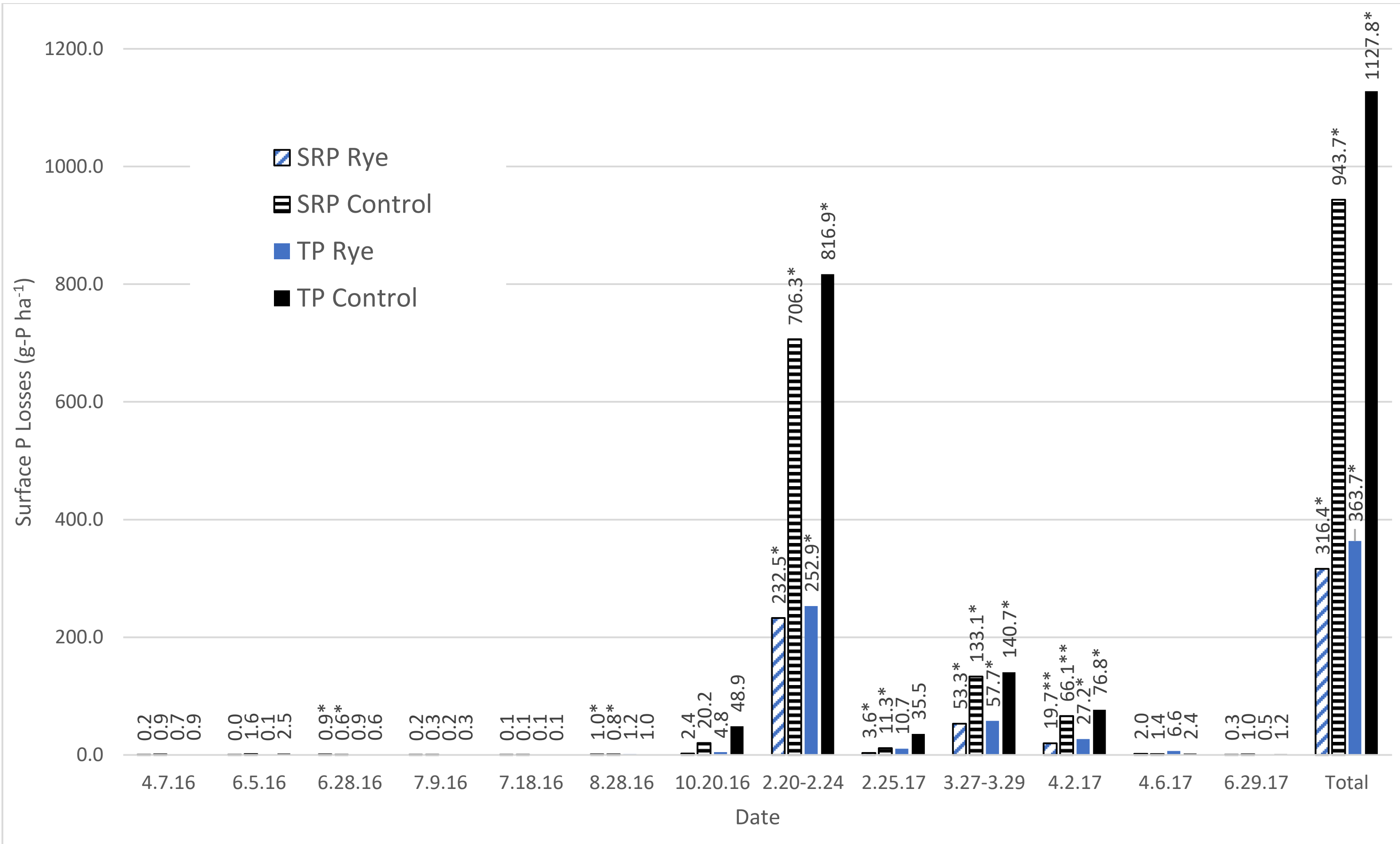


Figure 15. Surface phosphorus losses for every sampled event over the course of the study. Values with an * denote a significant difference ($p \leq$ 0.05) between cover and control treatments. A value with ** indicates mean values were trending towards significance ($p \leq$ 0.10).

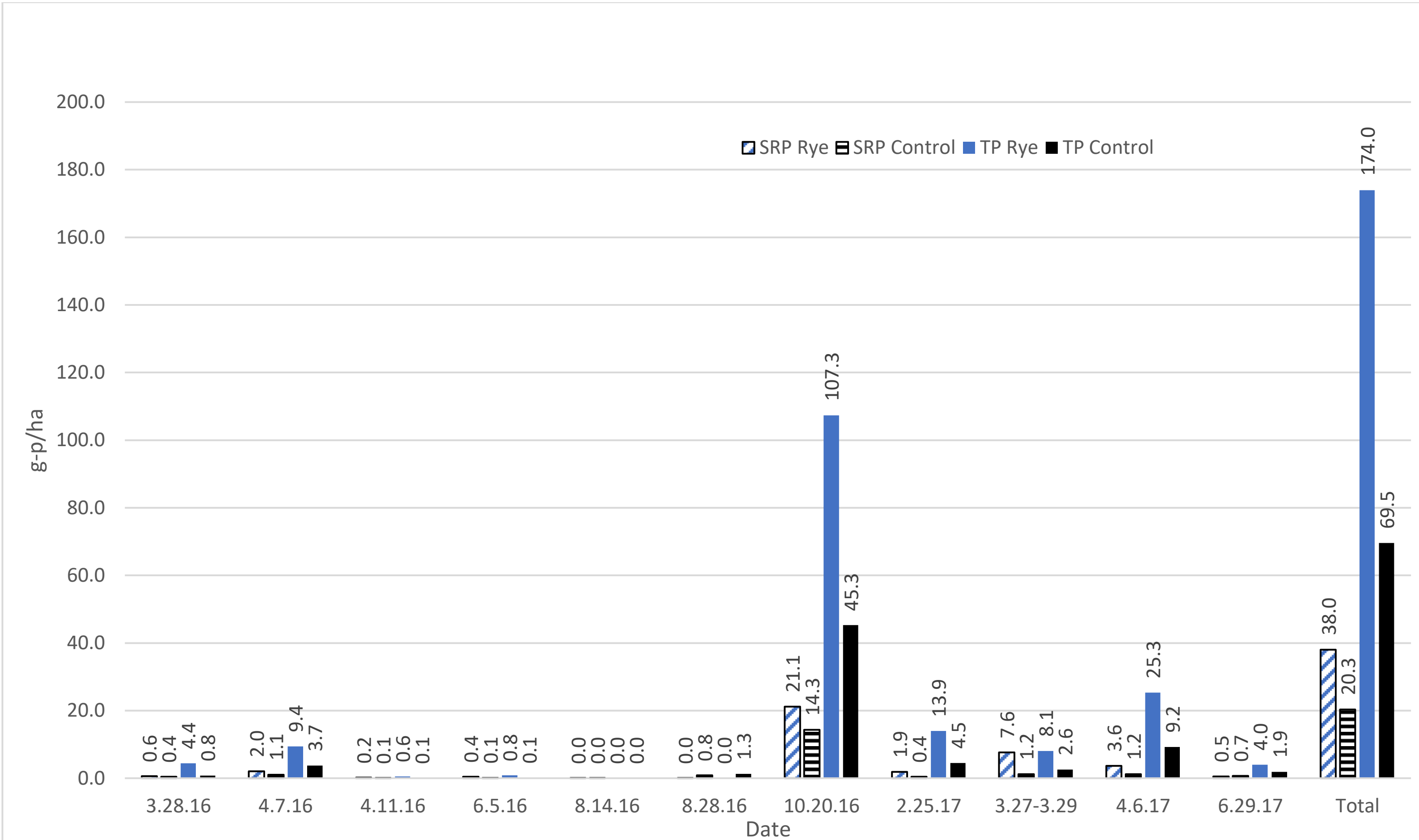


Figure 16. Tile Phosphorus losses for every sampled event over the course of the study. Values with an * denote a significant difference ($p \leq$ 0.05) between cover and control treatments. A value with ** indicates mean values were trending towards significance ($p \leq 0.10$).

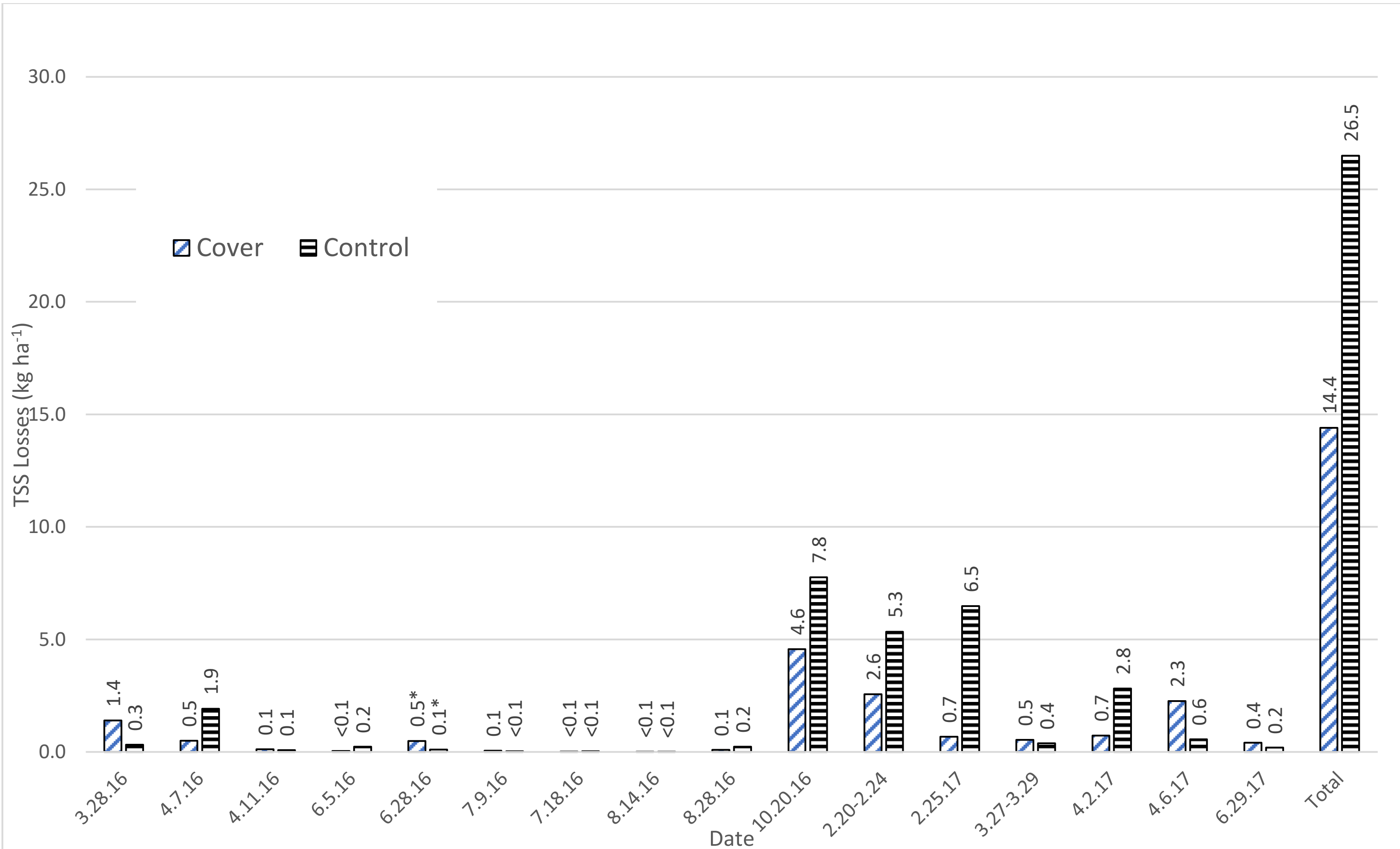


Figure 17. TSS losses for each sampled event over the course of the study (surface and tile combined). Values with an * denote a significant difference ($p \leq 0.05$) between cover and control treatments. A value with ** indicates mean values were trending towards significance ($p \leq 0.10$).

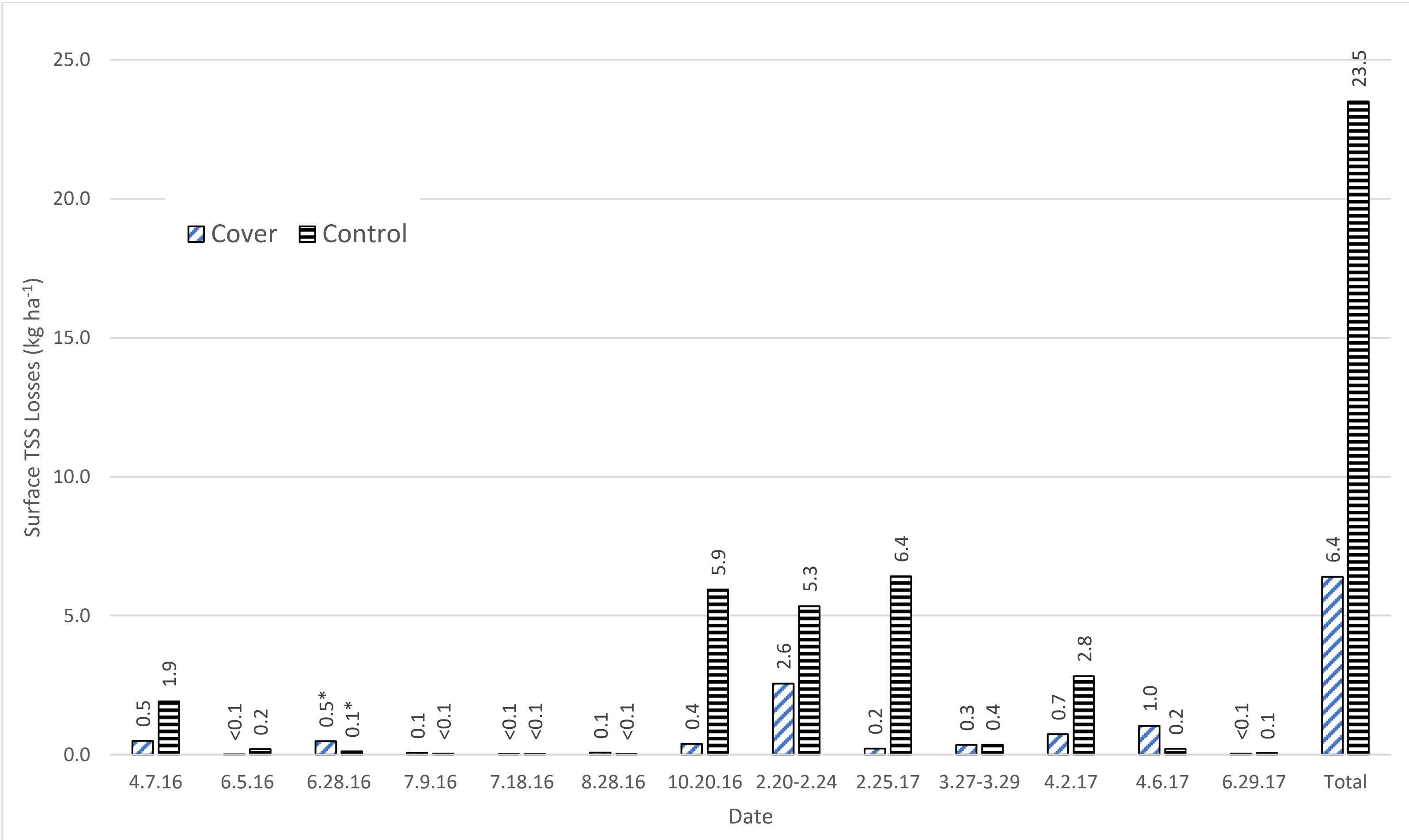


Figure 18. Surface TSS losses for the study duration. Values with an * denote a significant difference ($p \leq 0.05$) between cover and control treatments. A value with ** indicates mean values were trending towards significance ($p \leq 0.10$).

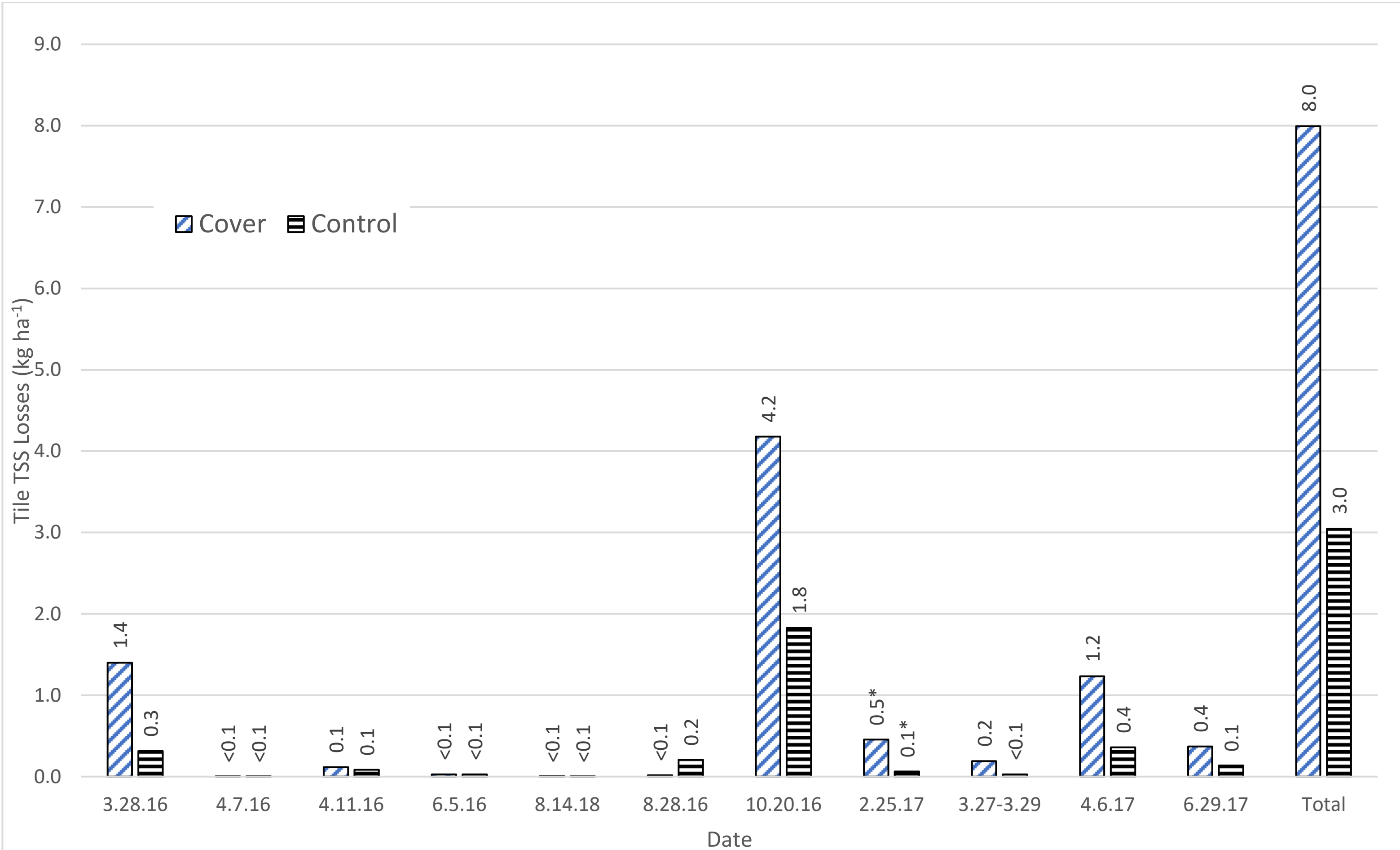


Figure 19. Tile TSS losses for the study duration. Values with an * denote a significant difference ($p \leq 0.05$) between cover and control treatments. A value with ** indicates mean values were trending towards significance ($p \leq 0.10$).

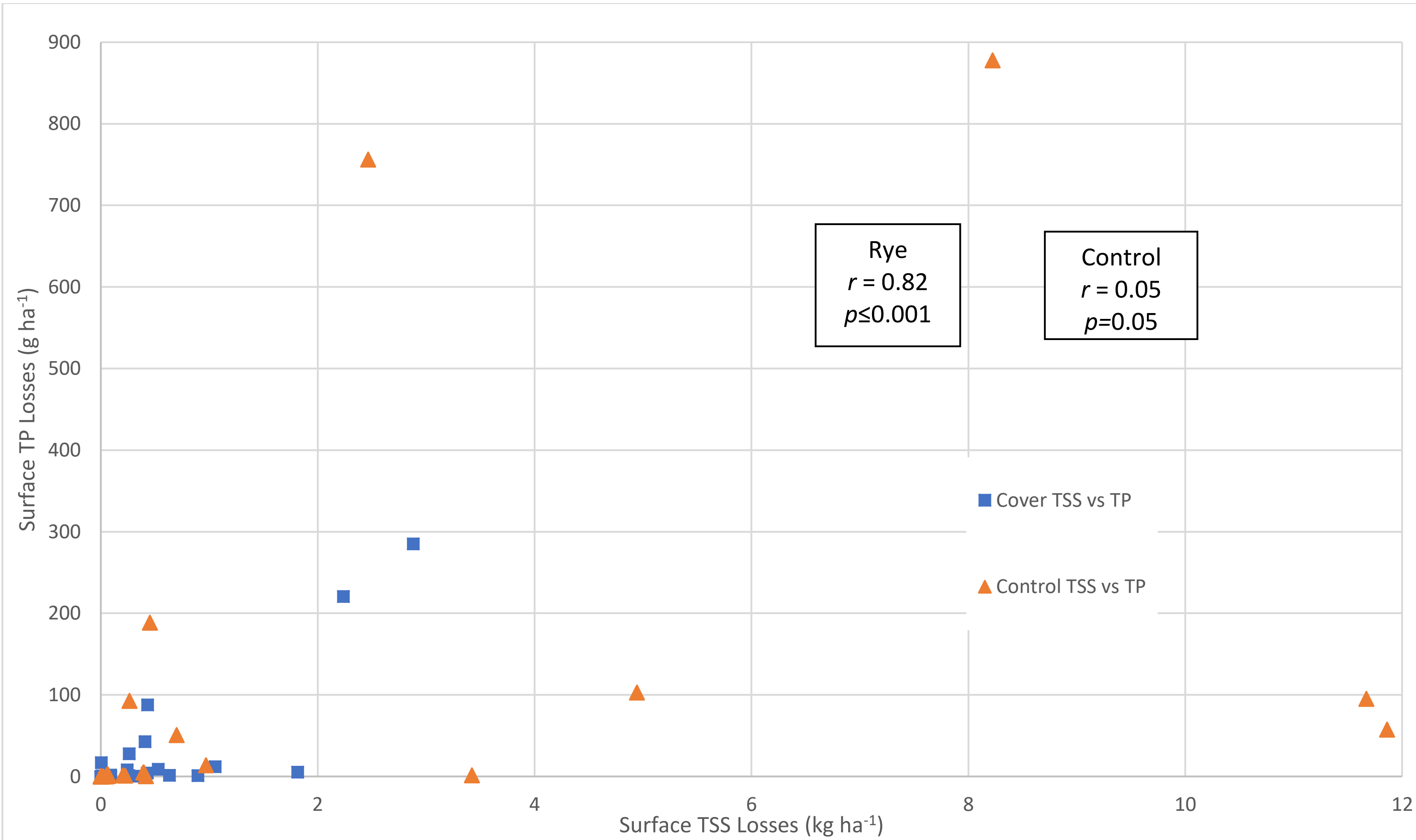


Figure 20. TP loads as a function of TSS loads in surface runoff for every sampled event for the study and Pearson correlation coefficients and *p*-values. Both treatments had significant correlation between TP and TSS losses.

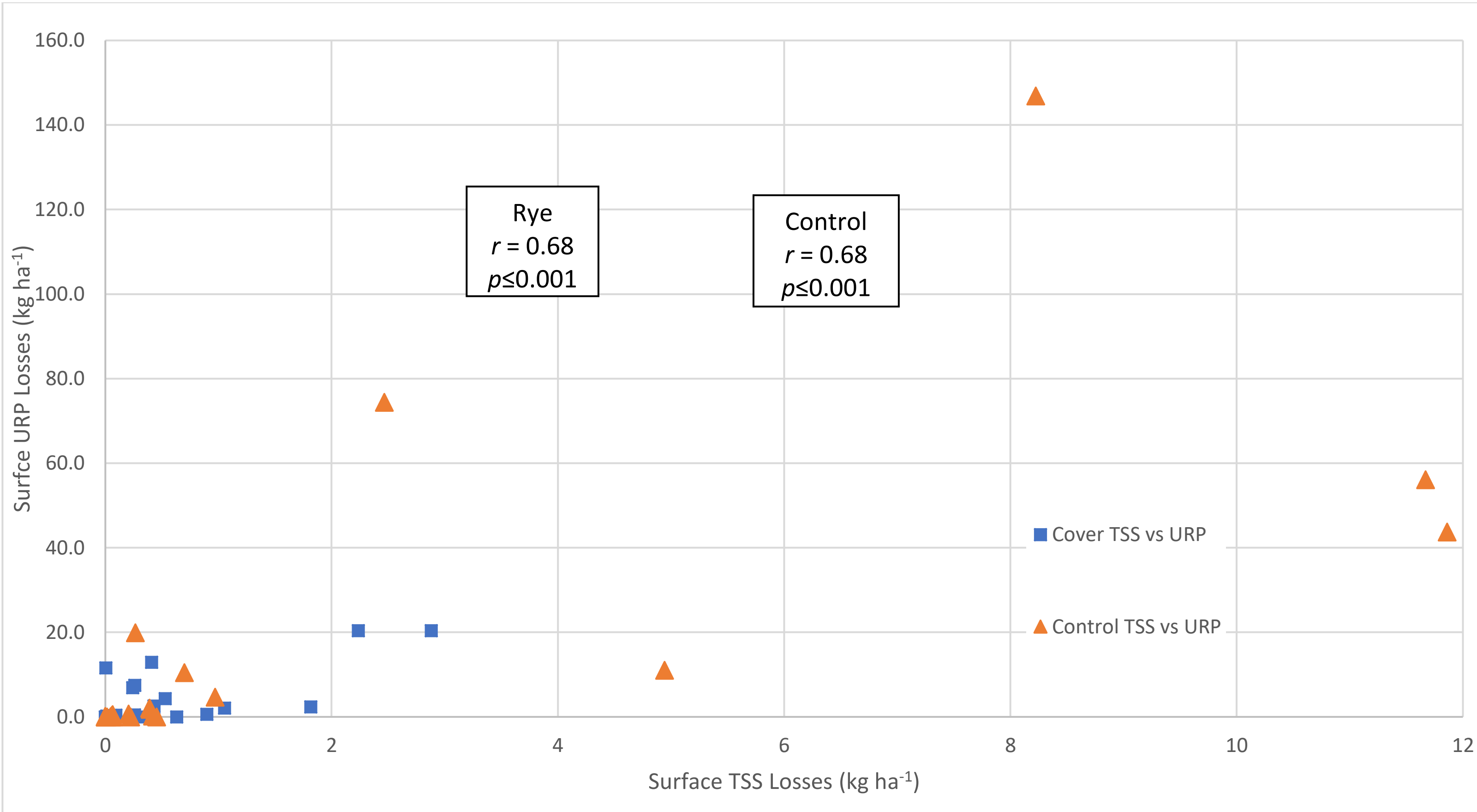


Figure 21. URP loads as a function of TSS loads in surface runoff for every sampled event for the study Pearson correlation coefficients and *p*-values. Both treatments had significant correlation between URP and TSS losses.

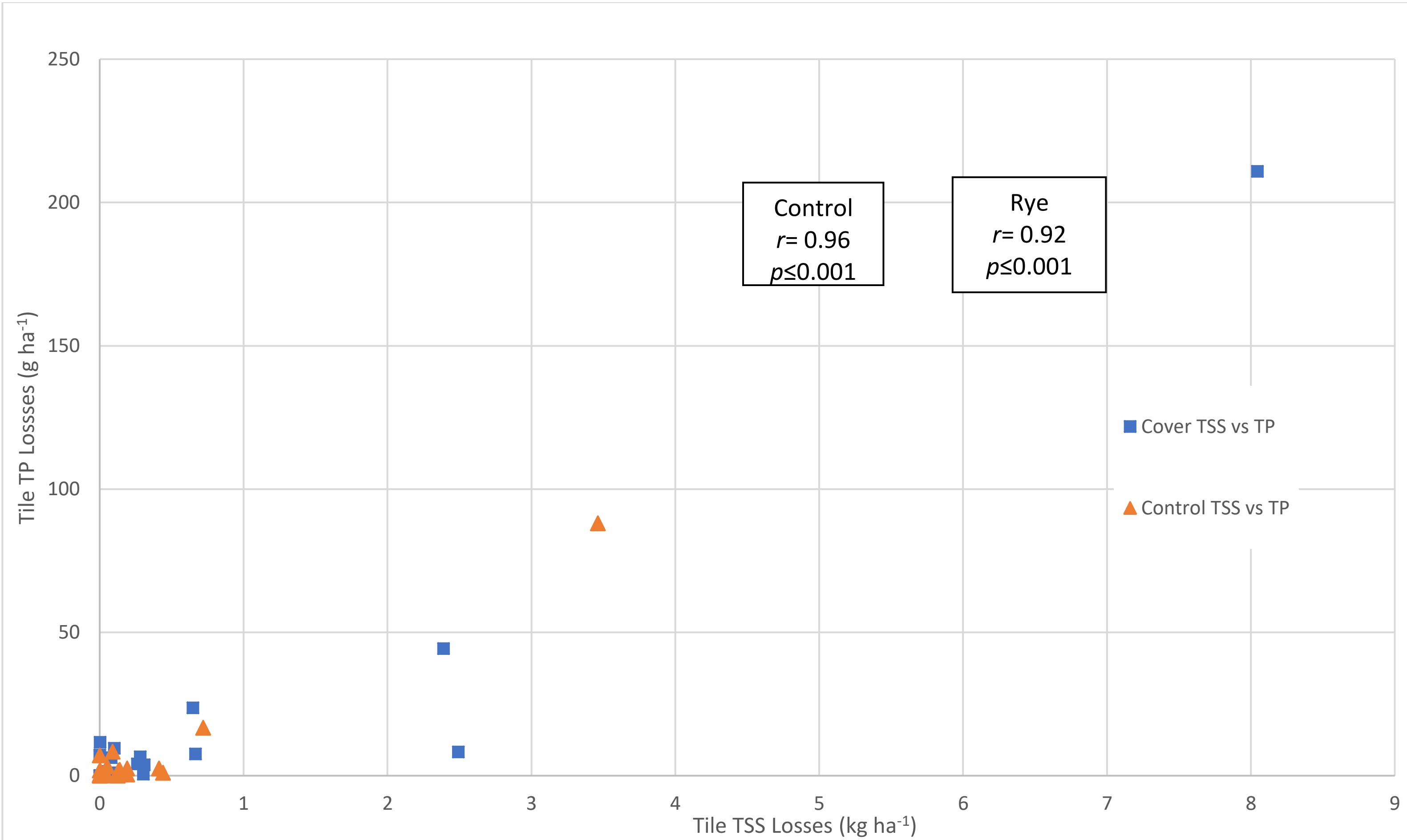


Figure 22. TP loads as a function of TSS loads in tile drains for every sampled event for the study and Pearson correlation coefficients and *p*-values. Both treatments had significant correlation between TP and TSS losses.

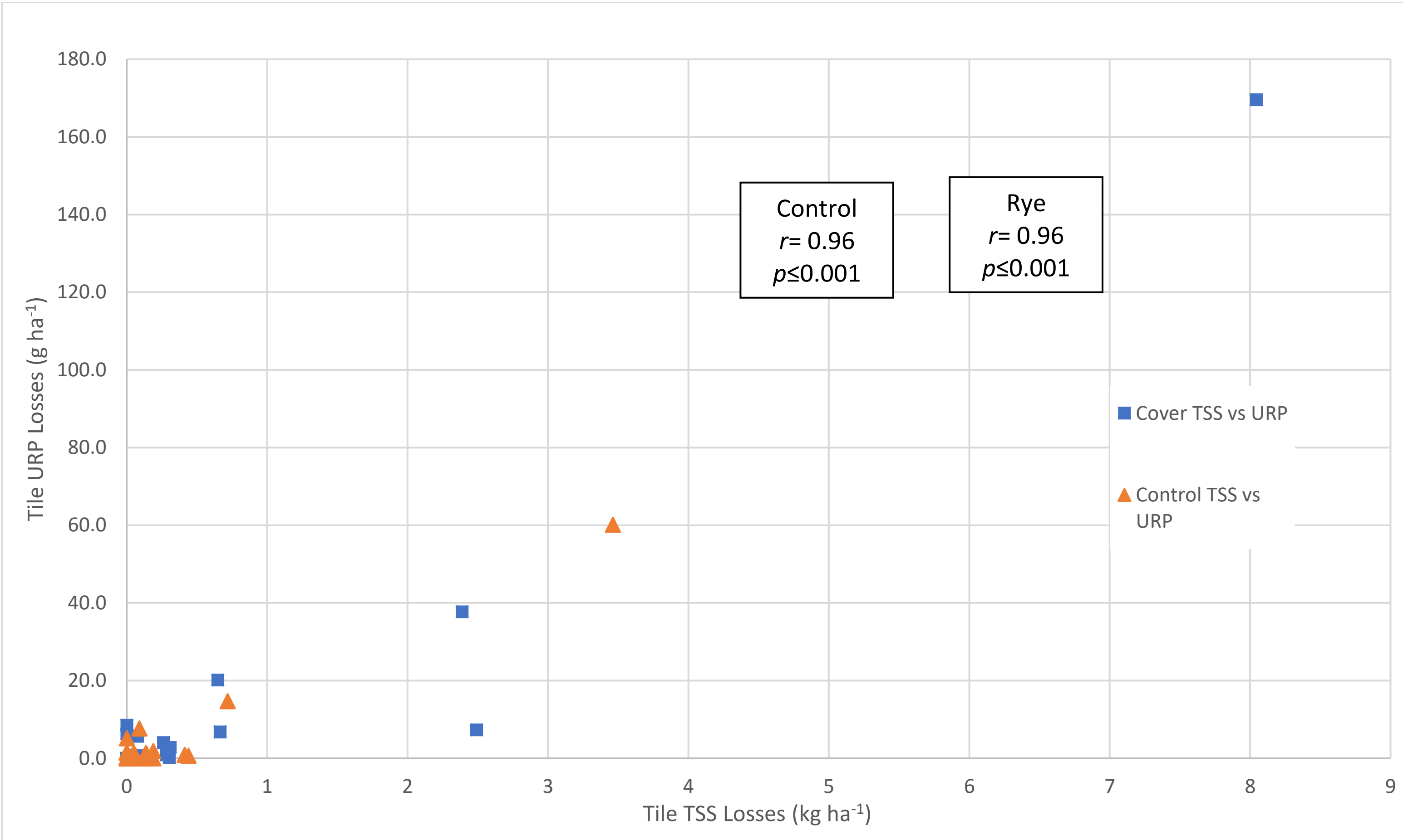


Figure 23. URP loads as a function of TSS loads in tile drains for every sampled event for the study and Pearson correlation coefficients and *p*-values. Both treatments had significant correlation between TP and TSS losses.

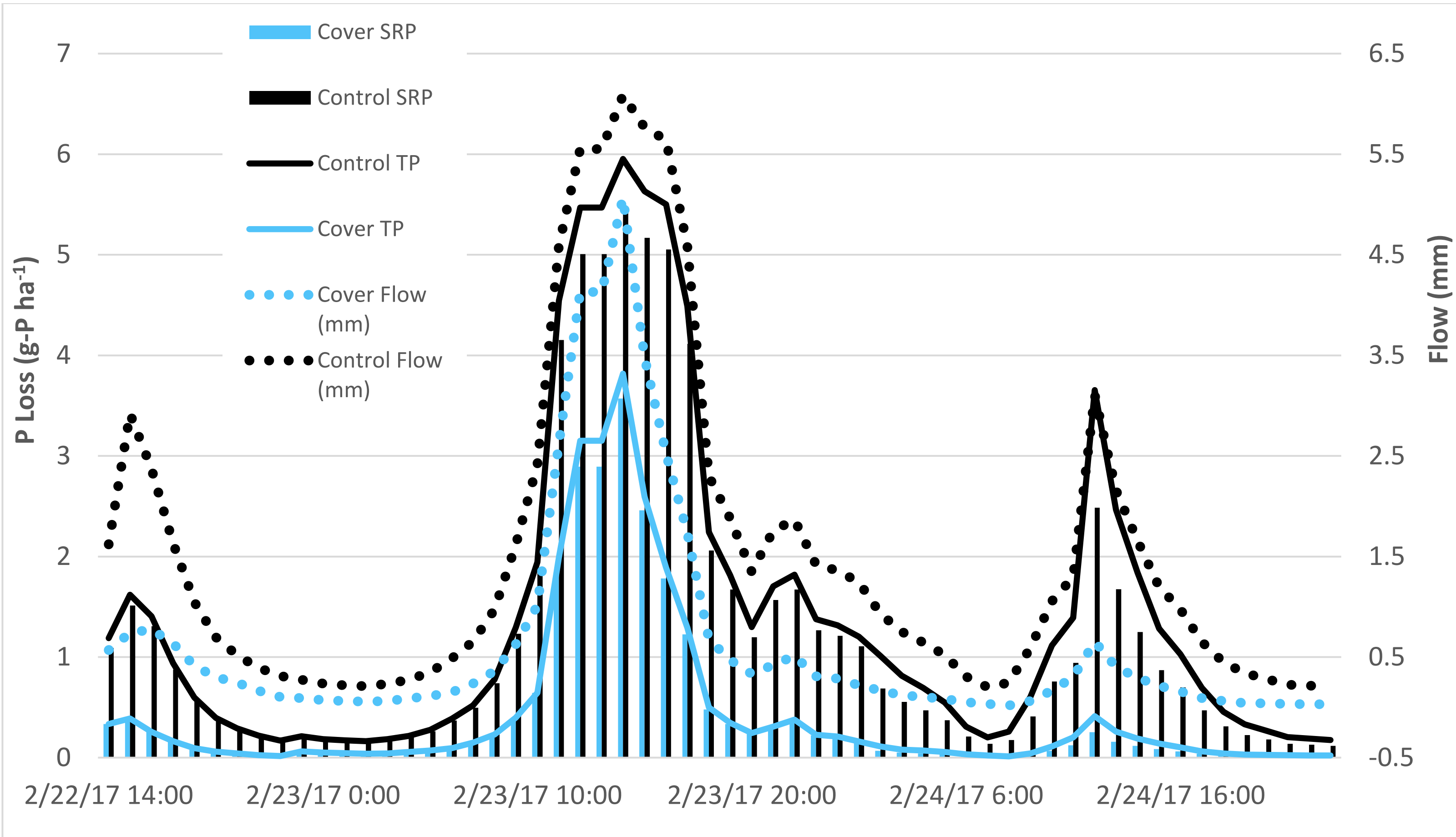


Figure 24. Surface runoff P losses for the first snowmelt of 2017 that started on 2/22/17 and lasted until 2/24/17. There were 131mm of water in the snowpack at the start of the event. Rye Plots had significantly less P exported compared to control. SRP made up 91% and 86% of all the TP that left the plots for cover and control plots, respectively.

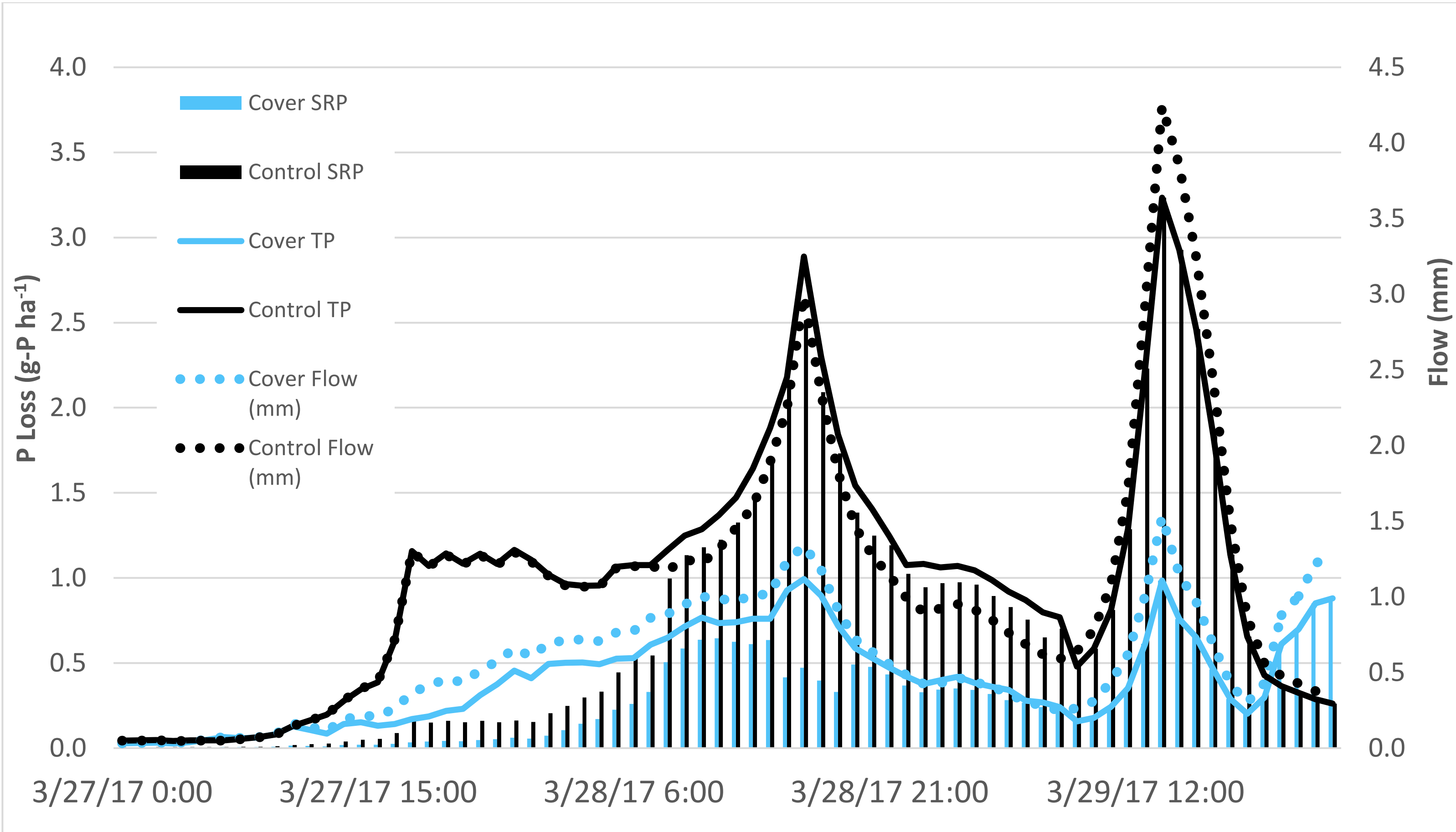


Figure 25. Surface runoff P losses in second snowmelt of the year that started on 3/27/17 and lasted until 3/29/17. There were 170mm of water in the snowpack at the start of the event. Rye plots had significantly less P exported compared to control. SRP made up 85% and 90% of all the TP that left the plots for cover and control plots, respectively.

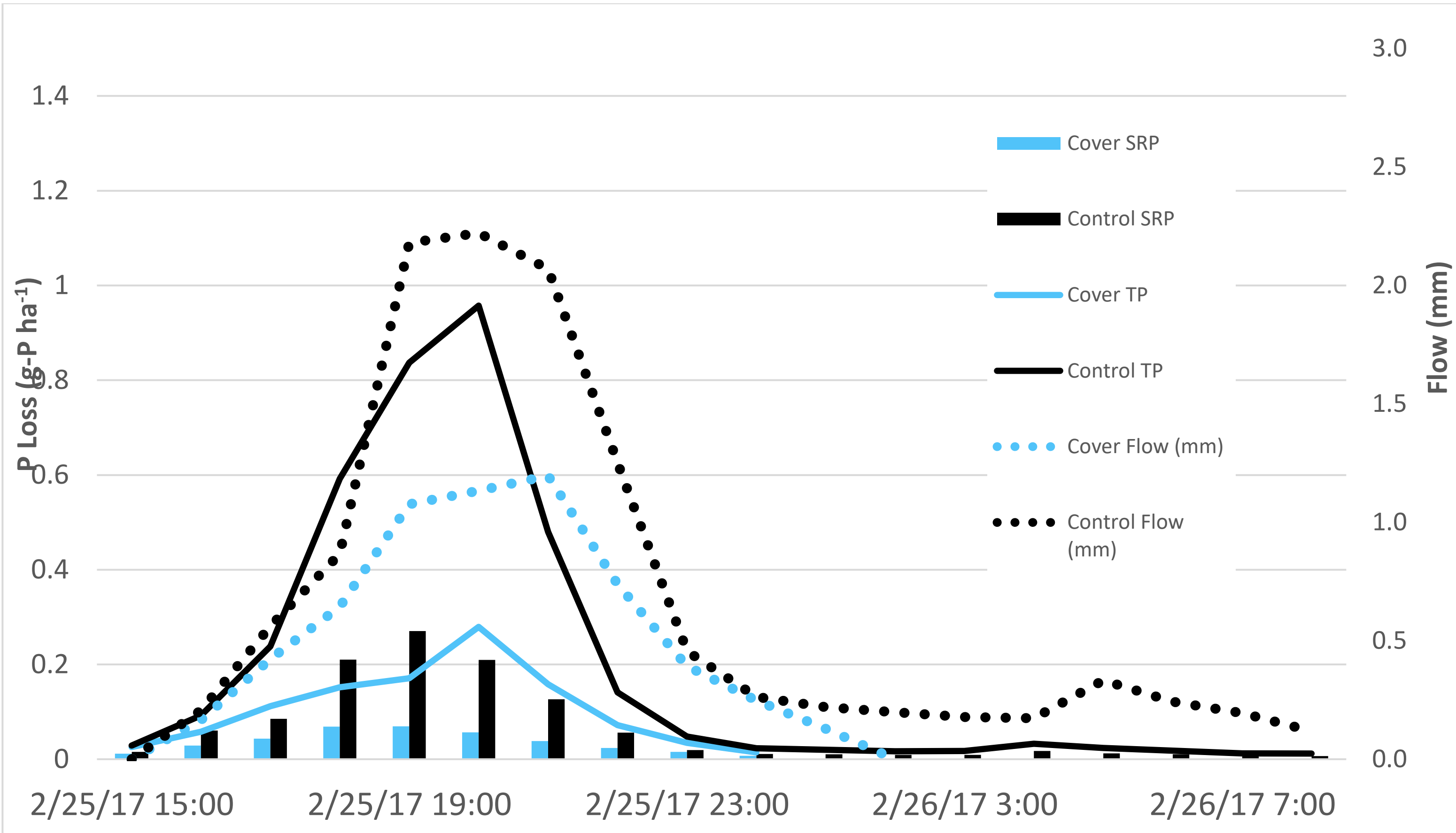


Figure 26. Surface runoff P losses in a 25mm rainstorm that occurred on 2/25/17 immediately following a week long snowmelt event. SRP losses were significantly reduced in the rye plots compared to the control. SRP made up 36% and 44% of all the TP that left the plots for rye plots and control plots, respectively.

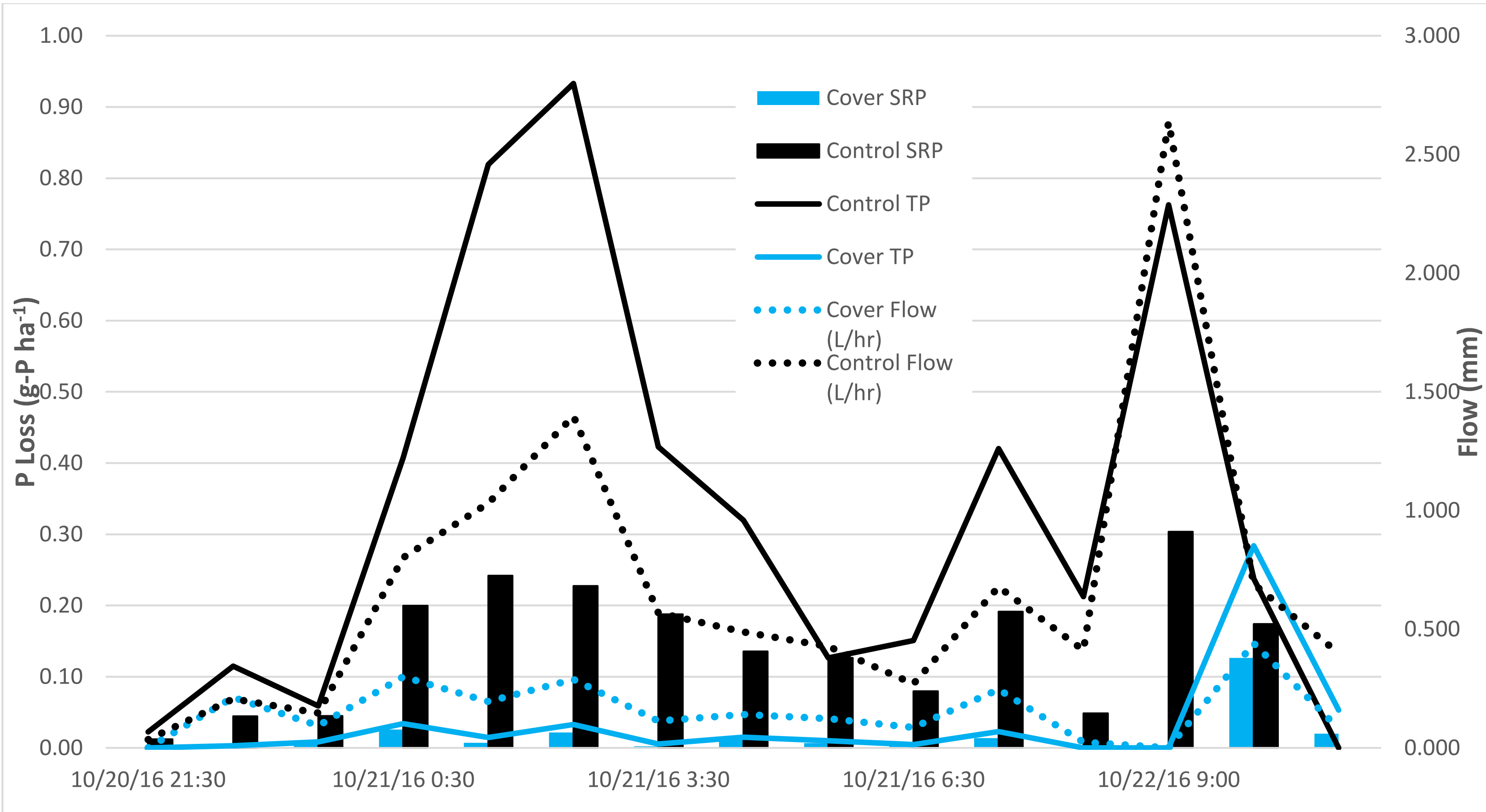


Figure 27. Surface runoff P losses from a 44mm rain storm that occurred 10 days after rye planting in 2016. SRP made up 23% and 28% of all the TP that left the plots for rye plots and control plots, respectively.

3.5. Nitrogen Export in Runoff

Mean TN and NO_3 (measured as NO_3-N but abbreviated as NO_3 for simplicity) export by treatment and pathway (surface and tile) for all events as well as cumulative export are presented in (Figure 28). Rye plots exported more N (cumulative NO_3 and TN loss = 15.7±1.2 kg-NO_3 ha^{-1} and 18.9± 1.3 kg-TN ha^{-1}) than control plots (cumulative NO_3 and TN loss = 14.9± 0.14 kg-NO_3 ha^{-1} and 21.5± 1.3 kg-TN ha^{-1}) but the difference was not significant. There was no difference in mean NO_3 export in surface runoff (Figure 29) between rye plots (0.5±.05 kg-NO_3 ha^{-1}) and control (0.8±0.9 kg-NO_3 ha^{-1}), however mean TN export in surface runoff was significantly lower for rye plots compared to control (2.3± 0.4 kg-TN ha^{-1} vs. 6.1± 1.1 kg-TN ha^{-1}; respectively). Most N export was through tile drains, accounting for 95 and 79% of cumulative NO_3 and TN export, respectively. There was no difference in mean NO_3 and TN export in tile drain flow (Figure 30) between rye plots (15.2 ±1.6 kg-NO_3 ha^{-1} and 16.6 ±1.7 kg-TN ha^{-1}) and control (14.1 ±1.4 kg-NO_3 ha^{-1} and 15.4 ±1.5 kg-TN ha^{-1}). While N export in tile drain flow did not differ by treatment, a five year study in Iowa found that winter rye reduced NO_3 losses in tile drainage by an average of 48%, however, in some years, they found that the rye cover crop released more NO_3 through tile drains than controls (Kaspar et al., 2012). The authors suggested a possible cause for this extra N from rye plots could be due to mineralization of rye biomass and subsequent nitrification and leaching of NO_3 to tile drain flows. This could help to explain the higher nitrate and TN losses observed in tile lines from rye plots, particularly since rye was left as mulch (e.g., 'green manure') in 2016. Other studies in the Midwest have reported from 37 to 61 % reductions in tile NO_3 export from using cover crops after corn

(Strock et al., 2004; Kaspar et al., 2007). While rye did not reduce N export in the present study, it is clear from the literature that a rye established after corn can result in substantially less N leaching and loss from tiles.

With respect to individual runoff events, the only statistically significant differences for surface runoff were two large snow melt events (Figure 29), 2.20-2.27.17 and 3.27-3.29.17. In the February snowmelt event (2/20-2/24/17), surface NO_3 was trending lower ($p \leq 0.055$) for rye (28 ±17 g-NO_3 ha^{-1} vs. 90 ±28 g-NO_3 ha^{-1}) while TN export for this same event was significantly lower ($p \leq 0.001$) for rye (1311 ±285 g-TN ha^{-1} compared to 3922 ±217 g-TN ha^{-1}). For the March snowmelt (3/27-3/29/17), both NO_3 and TN were significantly lower for rye plots compared to control (p=0.025 and $p \leq 0.001$ for rye and control, respectively; Figure 29). Given that winter rye is able to grow and survive in winter temperatures and was observed to be actively growing in the winter and early spring, the additional time between snowmelt events may have facilitated some uptake of N. Looking at rainfall and snowmelt events, 48% of NO_3 and 77% of TN in surface runoff was generated from the snowmelt events (Table 10). This once again demonstrates the importance of implementing BMPs such as cover crops for fields that have a high risk of N and P loss to surface water runoff.

Total N export was significantly correlated with TSS export in surface runoff for both treatments (Figure 31). Tile TN and TSS export in rye plots were correlated, but not in control plots (Figure 32). The correlation between TSS and TN in tile flow of rye plots could be related to: i) greater organic and inorganic N from rye biomass and leaching in rye plots ii) enhanced macropore flow/leaching to tiles in rye plots from no-till in year one and rye biomass, iii) release of N from organic matter accumulation/fine sediments in tile from previous study. With iii above, N export estimates for rye plots would be artificially elevated, thus masking potential N reduction due to the rye cover crop.

While rye did not reduce N loss in the present study, the literature has many examples of rye's ability to reduce NO_3 export from tile drains, with reductions ranging between 37-59% (Kaspar et al., 2007; Kaspar et al., 2012; Strock et al., 2004). This is important, since leaching is the main pathway for NO_3 loss form cropland (Feyereisen, 2006; Hively et al., 2009; Tonitto et al., 2006). To obtain the N reductions in tile lines it is key to have the rye planted by October 15th , particularly for northern latitudes (Feyereisen, 2006). As well as leaving the rye long enough in the spring to continue scavenging N. If left as a green manure the rye has the potential to mineralize and provide N to the following crop, this process may take up to 3 weeks until any benefits would be seen (Doran and Smith, 1991). With proper management a winter rye cover crop can reduce N export in tile drains and leaching to ground water. Limiting water quality degradation, health risks and saving the farmer money by keeping N in the field.

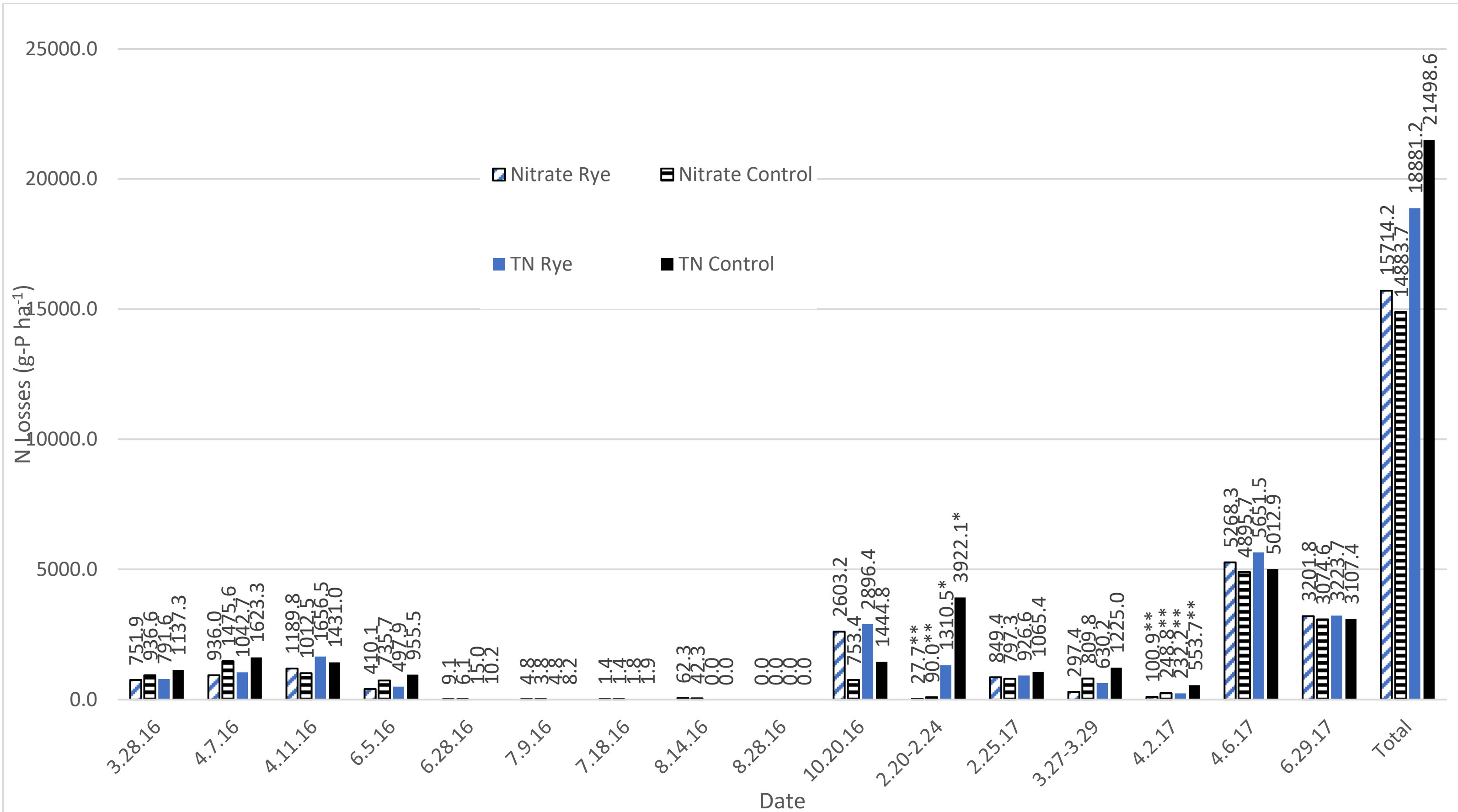


Figure 28. Nitrate and TN losses for both surface and tile drainage for every sampled event over the course of the study. Values with an * denote a significant difference (*p*≤ 0.05) between cover and control treatments. A value with ** indicates mean values were trending towards significance (*p*≤ 0.10).

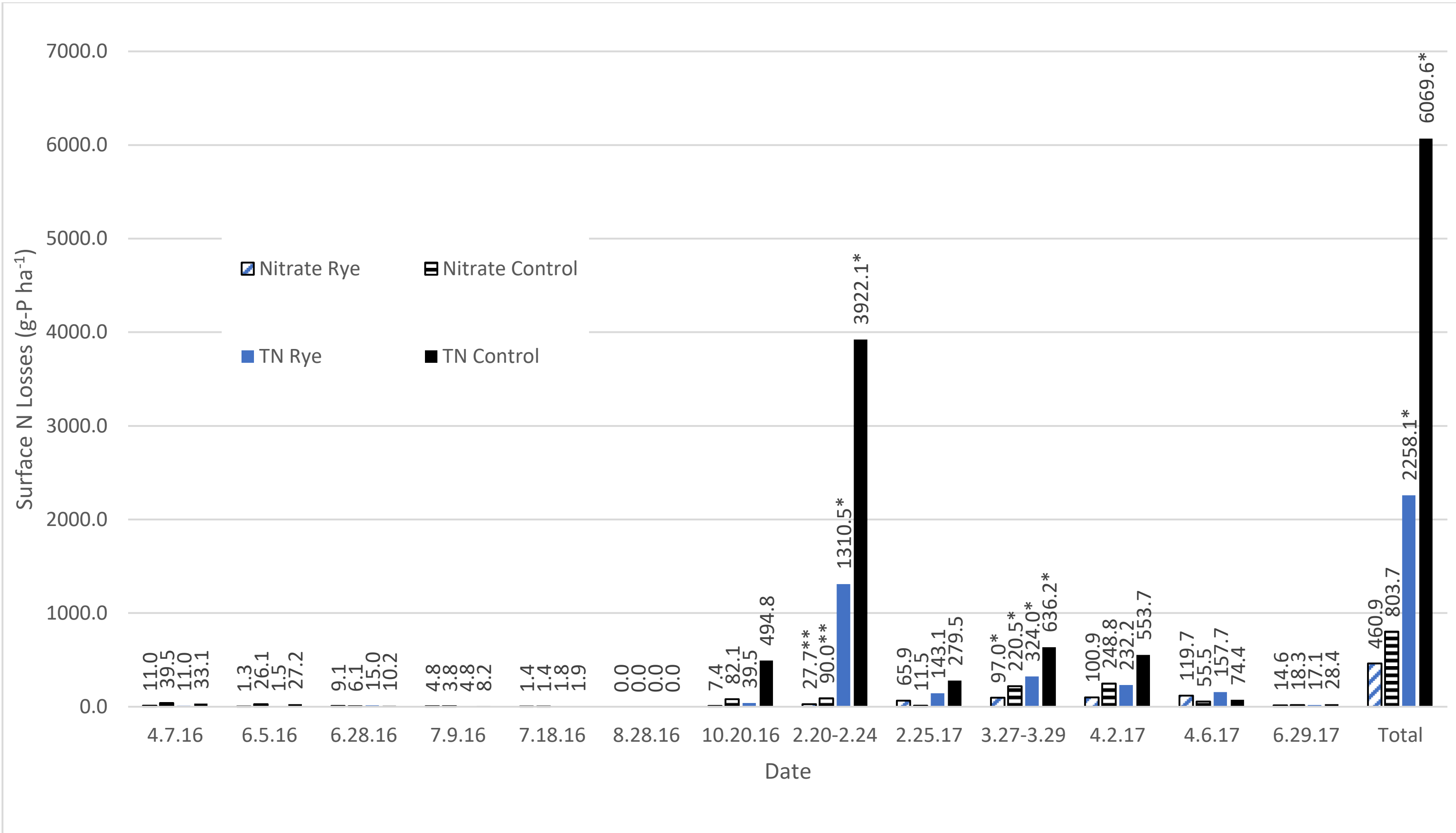


Figure 29. Nitrate and TN losses from surface runoff for every sampled event over the course of the study. Values with an * denote a significant difference ($p \leq 0.05$) between cover and control treatments. A value with ** indicates mean values were trending towards significance ($p \leq 0.10$).

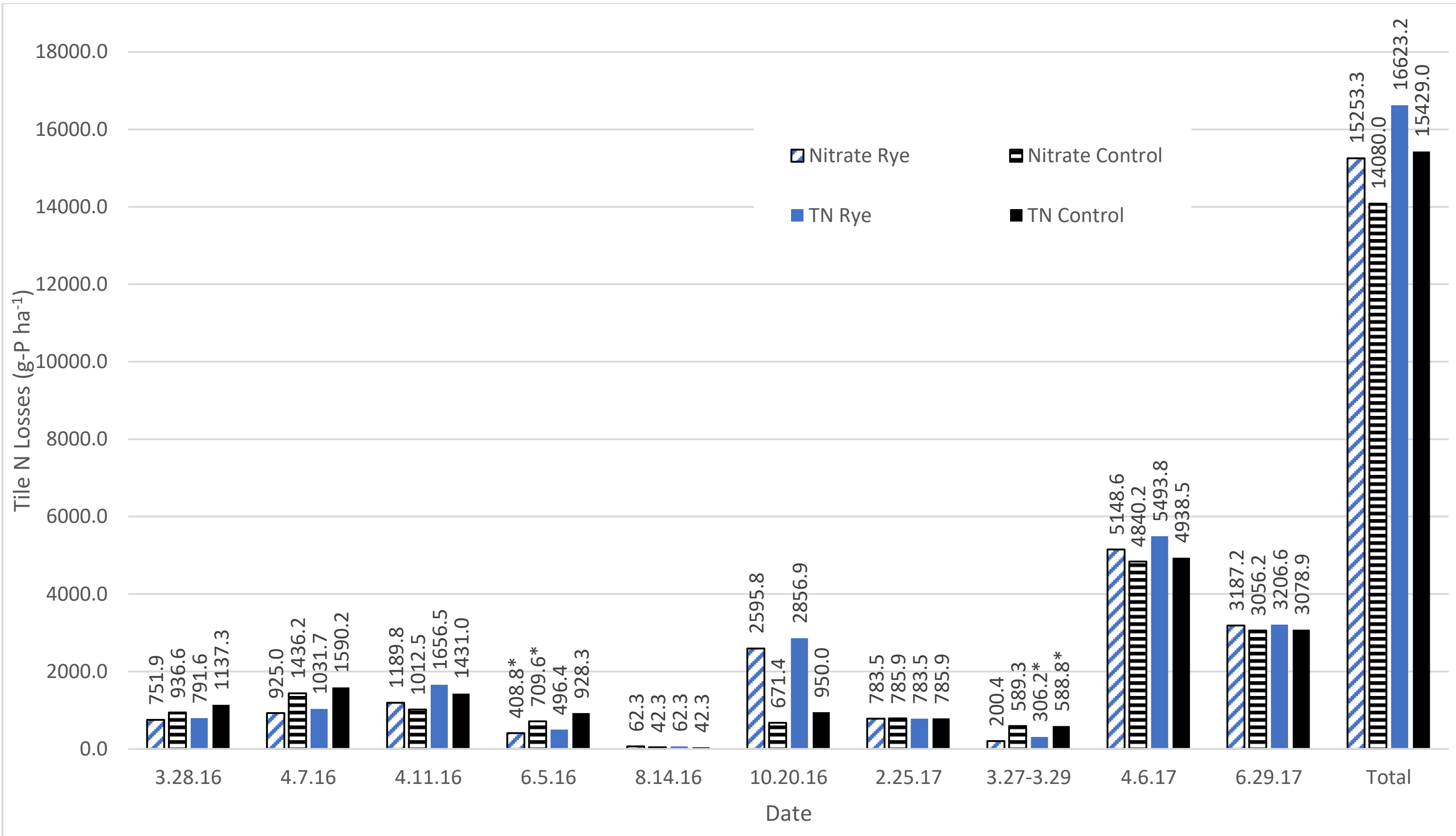


Figure 30. Nitrate and TN losses from tile drainage for every sampled event over the course of the study. Values with an * denote a significant difference ($p \leq 0.05$) between cover and control treatments. A value with ** indicates mean values were trending towards significance ($p \leq 0.10$).

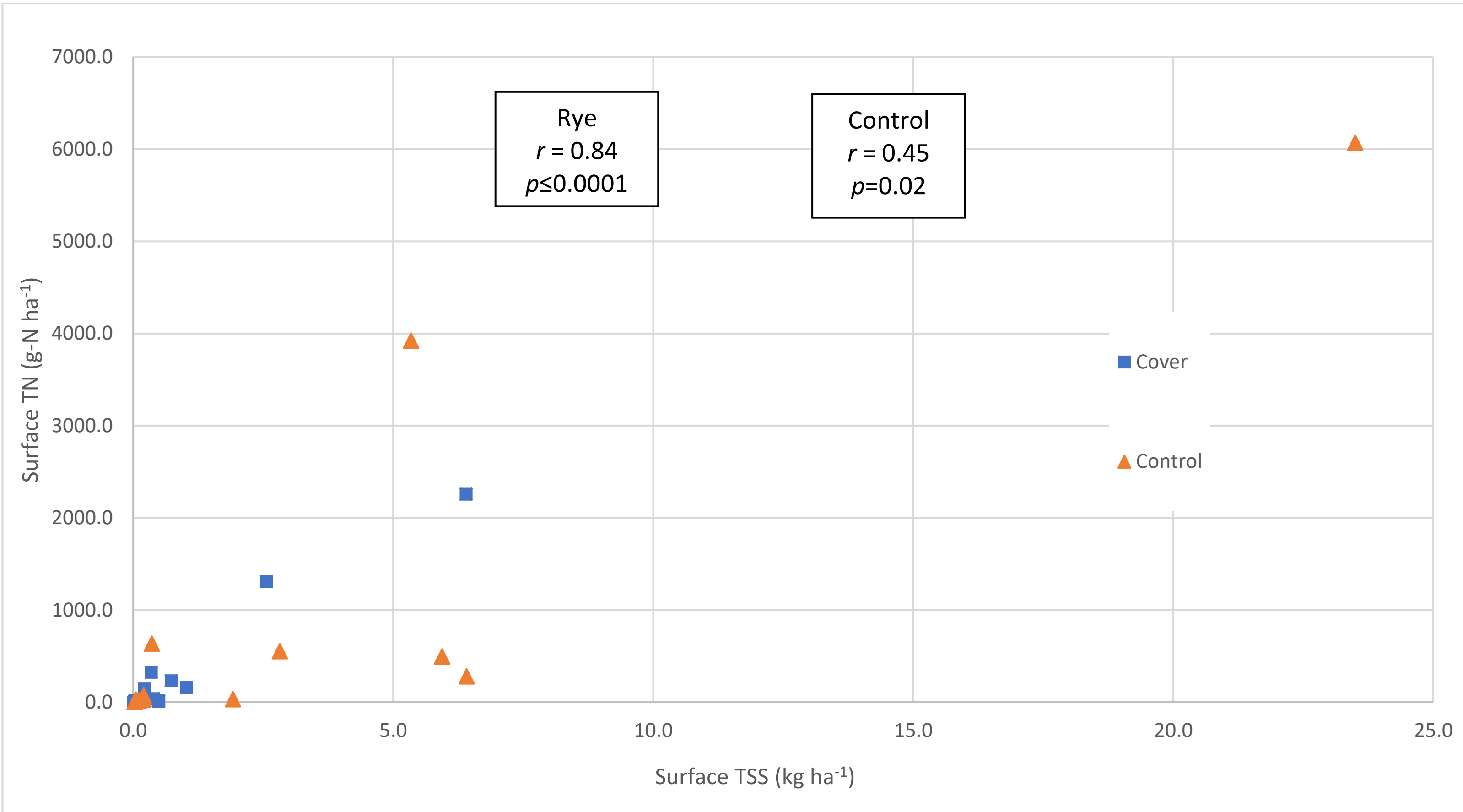


Figure 31. TN loads as a function of TSS loads in surface runoff for every sampled event for the study and Pearson correlation coefficients and *p*-values. Both treatments had significant correlation between TP and TSS losses.

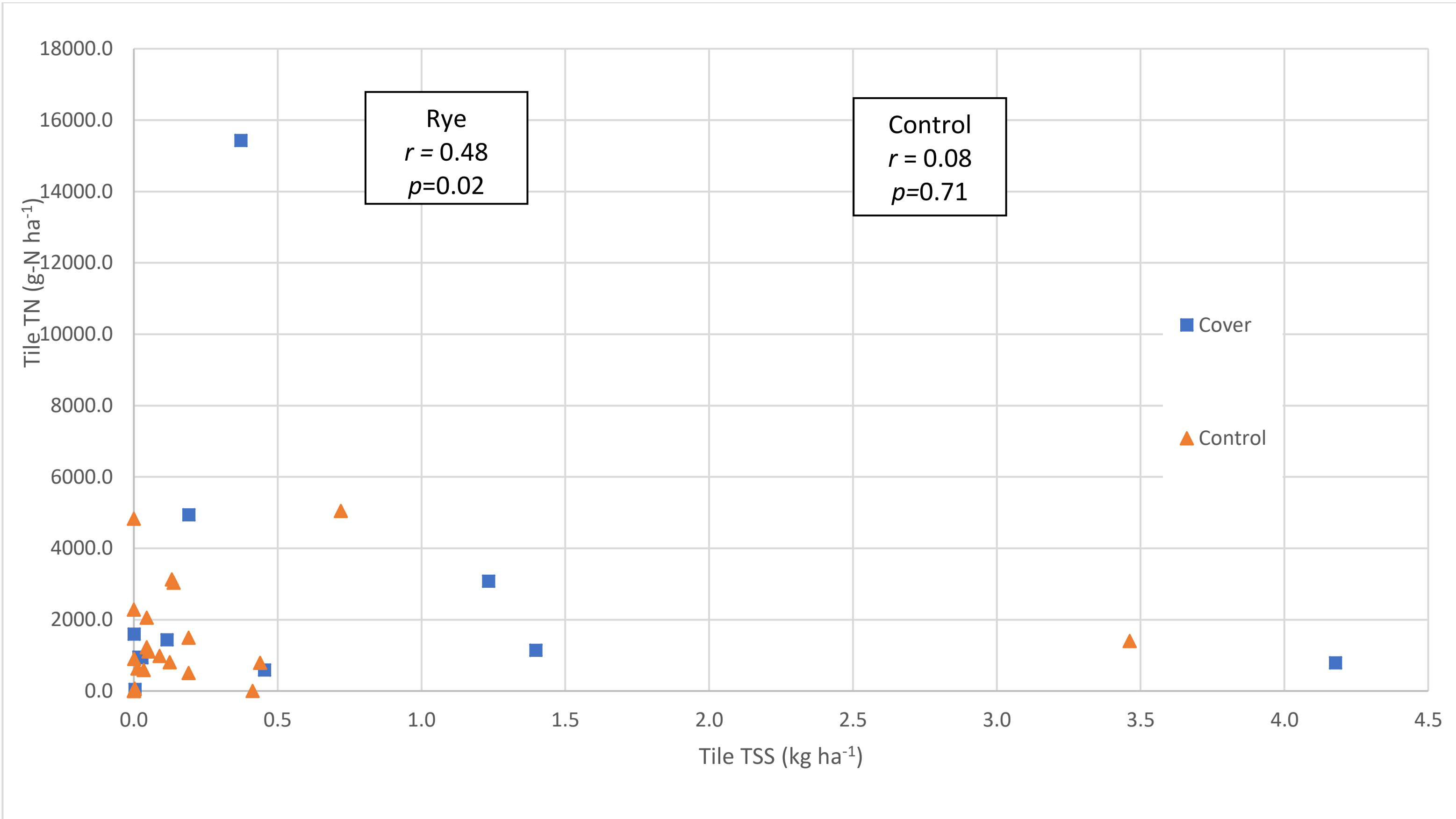


Figure 32. TN loads as a function of TSS loads in tile runoff for every sampled event for the study and Pearson correlation coefficients and *p*-values. Only the rye treatment had significant correlation between TN and TSS losses.

Table 10. Surface nitrogen losses in snowmelt and rainfall events. The reduction of P by using a winter rye cover crop was calculated by dividing the loss from the control by the loss from the rye. The percent of nitrate and TN generated by each type of event is shown in the last two rows. Nitrate is split evenly between the two types of events however 77% of the TN losses in surface runoff were generated from snowmelt events.

	Nitrate ($g\text{-}N\ ha^{-1}$)	TN ($g\text{-}N\ ha^{-1}$)
Total Cover	461	2258
Total Control	804	6070
Cover Rainfall	217	466
Control Rainfall	438	1437
Cover Snowmelt	244	1792
Control Snowmelt	366	4633
Reduction Rainfall	2.0 Fold	3.1 Fold
Reduction Snowmelt	1.5 Fold	2.6 Fold
% N generated from snowmelt	48.3	77.1
% N generated from rainfall	51.7	22.9

3.6. Forage Harvest

Winter rye yields increased over the course of the sampling period (Figure 33). In 2016, sampling started on the May 10 and continued to May 22, with 3 sampling dates. In 2017, sampling started on the 18th of May and ended on the 7th of June, with 4 sampling dates. Sampling started when the last leaf emerged just prior to flag leaf stage and starting to boot up and ended when the rye was headed out. Mean wet rye biomass yields in 2016 and 2017 for the last sampling date each spring were 7.2 and 14.3 Mg ha^{-1} (on a 35% dry matter basis). Average rye yields nearly doubled in 2017, which is probably due to UAN application and the latter harvest date in 2017.

In 2016, corn silage yields were significantly lower in rye plots (36.1 Mg ha^{-1}) compared to control (46.3 Mg ha^{-1}). In 2017, there was no significant yield difference between treatments (35.4 and 37.2 Mg ha^{-1} for rye and control, respectively; Table 11). The yield depression in 2016 may have been partly due to a lack of available N in rye plots from N immobilization in the rye biomass. Nitrogen immobilization was the primary mechanism through which a winter rye cover crop negatively affected corn silage yields (Doran and Smith, 1991; Duiker and Curran, 2005). It may take 1 to 3 weeks after termination of the winter rye before the rate of N mineralization over comes N immobilization and waiting these two-three weeks after termination might limit potential yield drag from using a winter rye cover crop (Doran and Smith, 1991; Ketterings et al., 2015). Corn was planted on the same day rye was terminated in 2016 and both treatments received the same amount of fertilizer N. Additional N applied as a starter at fertilizer is recommended to offset this N deficiency and potential yield drag associated N limitation (Crandall et al., 2005;

Ketterings et al., 2015; Miguez and Bollero, 2005). Another important and possibly overriding factor in the present study was the no-till planting of corn into standing rye with a planter that lacked adequate downforce to penetrate the rye biomass and ensure seed depth consistency. Visual observation during harvesting corn in 2016 indicated up to a 1/3 reduction in plant population density in rye plots, primarily due to shallow seed placement at planting. Therefore, the reduction in population was likely the primary reason for the yield depression observed for rye plots in 2016, which was probably exacerbated by N limitation in rye plots. In contrast to 2016, no significant yield differences were observed in 2017. Since rye plots were harvested for hay crop silage in 2017 and then disk harrowed, seed depth placement was not an issue in 2017 for rye plots as it was in 2016. Additionally, UAN was applied at green up which may have added some residual N for corn uptake not available in 2016.

Total forage harvested (rye + corn vs. corn) was not significantly different in 2016, however significantly more forage was produced from rye +corn silage plots in 2017 (Table 11). While the difference in total forage produced was relatively small, other studies on dairy farms across NY state have observed total forage increase of 17-51% relative to growing corn silage only (Ketterings et al., 2015). If the goal is harvesting winter rye for forage as opposed to using it as a green manure, then it is advisable to apply additional N at green up (Miguez and Bollero, 2005). From results presented here, it appears winter rye can successfully be used as a double crop with corn silage provided adequate planting/tillage and soil N fertility as was demonstrated in 2017.

3.6.1. Field N and P Mass Balance Estimates

The chemical analysis of corn and rye allowed us to calculate how much N and P was removed by each treatment. Crude protein and P content for rye and corn (Table 12), were consistent with NY state averages (8.2% CP for corn silage, 14% CP for winter rye, 0.23% P for corn silage and 0.35% P for winter rye (DairyOne, 2018). Mass of N and P removed by corn silage and rye was also estimated (Table 12). Phosphorus and N removal by corn silage was consistent with regional averages of 36 kg-P ha^{-1} (Cela et al., 2014) and 94-210 kg-N ha^{-1} (Jokela et al., 2014). Not surprisingly, corn and rye nutrient uptake was greater than corn nutrient uptake alone (corn left bare) and in 2017 rye plots had significantly greater N uptake compared to the control (Table 13). Rye uptake of N was slightly higher than published data (46-144 vs 36-60 kg-N ha^{-1}) (Sainju and Singh, 1997) however, rye in our study had relatively large yields in 2017 due to later harvesting and UAN application which may have supplied additional N as previously mentioned. Much of the literature on rye cover crops is focused on potential N contribution to the next crop (e.g., managing rye as a green manure for N mineralization) rather than on total N taken up at later stages of growth such as was the case in the present study.

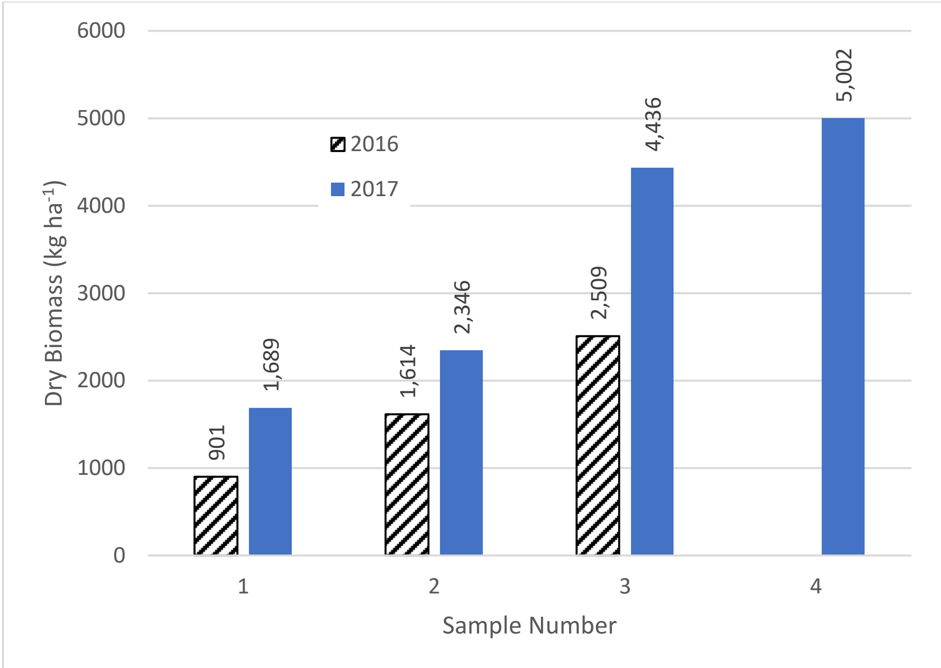


Figure 33. Winter Rye harvest yields in kg ha^{-1} for 2016 and 2017, sampling started when rye was at flag leaf stage and concluded once rye was at boot stage.

Table 11. Total biomass harvested from plots for both years of study on a mg ha^{-1}. Values with an * denote a significant difference (*p* ≤ 0.05) in mean values between cover and control treatments

	Cover Crop Mg ha^{-1} (35%DM basis)	Corn Silage Cover Mg ha^{-1} (35%DM basis)	Corn Silage Control Mg ha^{-1} (35%DM basis)	Total Forage Rye and Corn Silage Mg ha^{-1} (35%DM basis)	Total Forage Corn Silage Mg ha^{-1} (35%DM basis)
2016	2.5	36.08^{a}	46.31^{b}	38.6^{a}	36.08^{a}
2017	5.0	35.4^{a}	37.2^{a}	40.4^{a}	37.2^{b}

Table 12. Nitrogen and P content in forages and mass of N and P removed (kg ha^{-1}).

	%CP	%P	Yields Mg ha^{-1} (DM basis)	Kg-N ha^{-1} Removed	kg-P ha^{-1} Removed
2016 Corn (Rye Treatment)	9.6	0.2	12.6	194.7	26.1
2016 Corn Control	9.2	0.2	16.2	237.4	33.4
2017 Corn (Rye Treatment)	7.6	0.2	12.4	149.8	26.6
2017 Corn (Control)	8.0	0.2	13.0	165.7	29.3
2016 Rye	11.7	0.3	2.5	47.8	8.8
2017 Rye	18.3	0.4	5.0	146.0	19.3

Table 13. Total N and P in forage in kg ha^{-1} by treatments. An * denotes a significant difference between treatments, $p \leq 0.05$.

	Rye + Corn Removal	Corn Removal	P-value
2016 (kg-N ha^{-1})	242.5	237.4	0.19
2017 (kg-N ha^{-1})	295.8*	165.7*	0.002
2016 (kg-P ha^{-1})	40.7	33.4	0.44
2017 (kg-P ha^{-1})	36.3	29.3	0.38

3.7. Mass Balance

Based on estimates of N and P inputs (fertilizer, manure) and outputs (forage harvest, runoff losses), a simple conceptual mass balance based on measured N and P fluxes was calculated and depicted (Figure 34). There was a total of 217.2 kg-N ha^{-1} applied to control plots, 287.2 kg-N ha^{-1} applied to rye plots and 67.7 kg-P ha^{-1} applied to all plots. The rye in 2016 was left as a green manure with 47.7 kg-N ha^{-1} and 8.8 kg-P ha^{-1} in aboveground biomass. The N fertilizer replacement value (NFRV) of winter rye is often zero or negative, after three weeks, the rate of N mineralization generally exceeds N immobilization (Doran and Smith, 1991). While rye did not likely act as a source of N for corn during the early season, it may have contributed to some N release later in the season around the time additional N is applied (late June/early July). Nutrients lost from the plots through surface runoff and tile drainage were small percentages of the total. For the entire study duration, rye plots lost 18.9 kg-N ha^{-1} and 0.5 kg-P ha^{-1} and control plots lost 21.5 kg-N ha^{-1} and 1.2 kg-P ha^{-1}. This accounted for 4.4%, 0.7%, 6.9%, and 1.8% respectively, of the total added. The rye harvest in 2017 removed 34% of TN applied and 25.2% of the total P applied. For both 2016 and 2017, corn harvest from rye plots removed 80% of all N applied and 68.9% of all P applied. The control plots removed 128.9% of all N applied and 92.6% of all P applied. The total amount of N removed from the plots (runoff + crop removal) was greater than 100% of what was applied. This excess N removal is likely due to organic matter mineralization and release of ammonium and subsequent nitrification. A possible explanation to the larger amount of N scavenged by control plots could be that rye plots received an additional treatment of UAN in 2017. For both treatments, there was a slight P surplus after all inputs and outputs were calculated this could potentially explain the increase in STP level (Table 7). Rye plots removed 94.7% of all the P applied and control plots removed 94.4% of all the P applied and an average of 3.5 kg-P ha^{-1} left in the plots at the end of the study. The average STP increase was 2.5 kg-P ha^{-1}; since STP is an index of agronomic P availability and some of the P in manure was organic, estimates of surplus P in plots in relation to the relative increase in STP appear reasonable. Additionally, some of applied P will be irreversibly sorbed, particularly as soil pH values decrease below <6.5.

Based on the above estimates, much of the applied N and P was removed by harvesting forage. While only a small percentage left via runoff, many runoff concentrations were at or above eutrophication levels for P, particularly in surface runoff. While the total amount lost to surface waters is a small portion of that applied, there is still risk of eutrophication of surface waters. In lakes like Lake Champlain, maintaining concentrations <10 mg SRP L^{-1} and 50 mg TP L^{-1} is considered critical to prevent eutrophication. SRP concentrations in the snowmelt events averaged 700 ug L^{-1}, 14 times more concentrated than the limit set by the EPA. It is important to note that these edge-of-field runoff concentrations are a worst case scenario, since dilution, mixing and P sorption processes occur between the field edge and transport to a surface waters. However, it is clear from the present study and others that agricultural fields can still be a significant source of P losses, contributing to eutrophication risk.

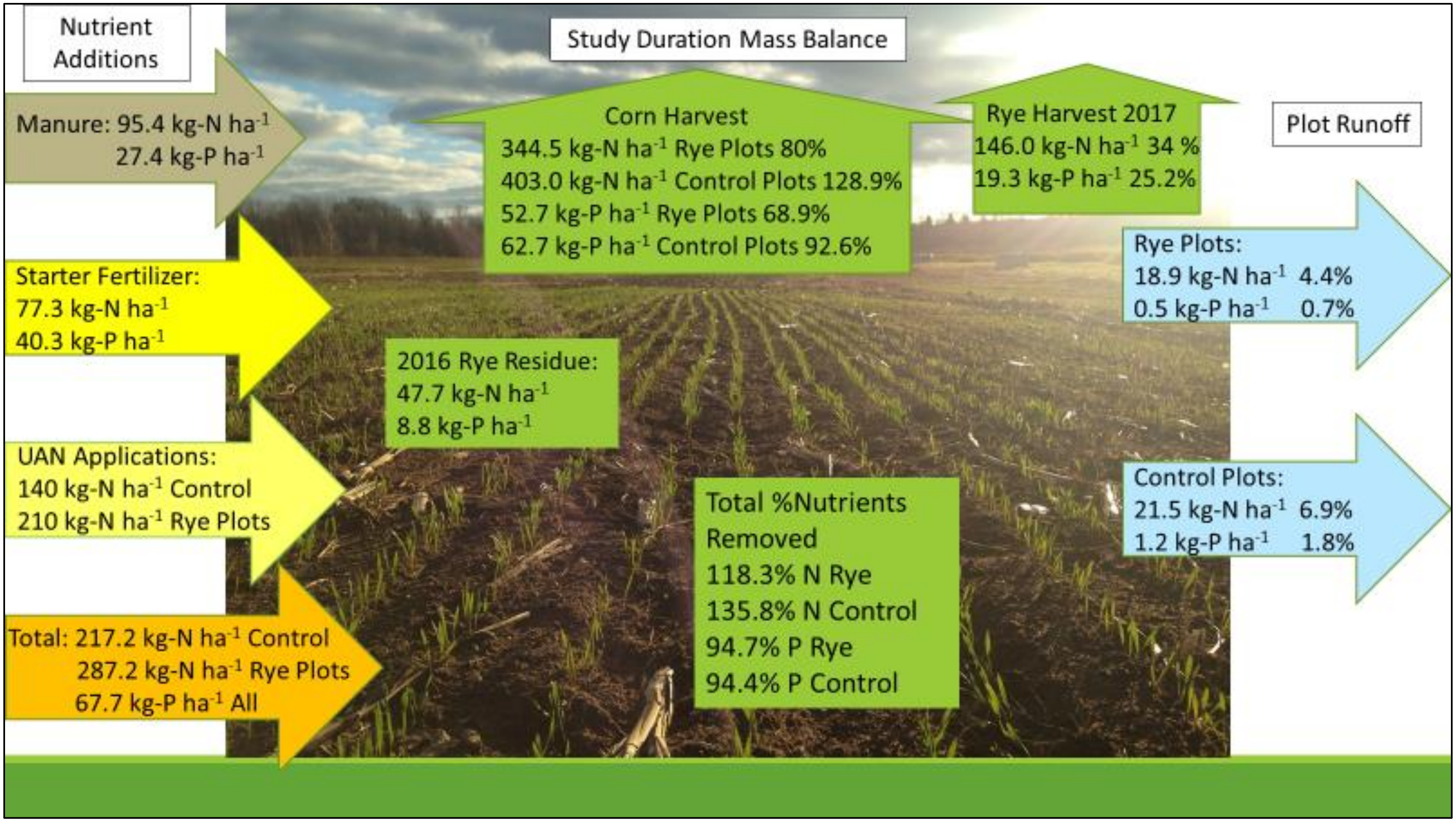


Figure 34. Study duration field mass balance N and P estimates by treatment (treatment means expressed as kg ha^{-1}), percentage of the total N and P added, relative to the amount of N and P removed (%) by pathway (runoff, harvest, combined).

3.9. Conclusion

The results from this study indicate that using winter rye as a cover crop in a corn silage rotation significantly decreased surface runoff and P exported in surface runoff. When managed as a double crop (rye harvested as a hay crop forage followed by corn) rye plots also produced more total forage (rye + corn biomass) harvested. Two out of the three hypotheses were supported by the data: Surface runoff volumes were lower in cover cropped plots, and total forage harvested from cover cropped plots was greater. The first hypothesis, that mean nutrient losses will be lower in cover cropped plots, was only partly supported by the data collected. Only surface runoff losses of, SRP, TP, and TN losses were significantly lower in rye plots. In contrast to surface runoff, there were few significant differences for tile drain runoff flows, though tile N and P losses were consistently greater from the rye plots. Based on the literature, this is atypical for N losses and there is limited research on P loss reductions in tile lines by using a cover crop. The lack of significance observed in tile drains for N and P losses could be attributed to the artifact from the previous study, as well as the potential that the winter rye increased infiltration rates combined with no-till in 2016 led to preferential flow of N and P to tile lines following root channels and macropores.

The data collected over the past two years shows that the main pathway for loss of P was via surface runoff (97% SRP and 97% TP). With the ability of a winter rye cover crop to significantly reduce P losses through this pathway, using winter rye to help control P losses during the non-growing season is recommended, particularly where particulate-bound P is an important source. Results also indicated that just a few snowmelt events can contribute the vast majority of P losses for the year (96% of SRP and 92% of TP were lost in snowmelt events), emphasizing the need to implement management techniques to mitigate snowmelt-driven P losses. Results from this study indicate that winter rye can significantly reduce P loss in surface runoff during the growing and non-growing season. In addition, farms have the option of harvesting rye as a forage crop and double cropping with corn. In this situation, more total forage can also be produced for the farm in addition to offering environmental conservation and water quality benefits. I like to say that cover crops are like a fridge. Excess nutrients in the fall can be stored in the cover crop biomass and used to feed the next annual crop or harvested as forage to feed animals, they keep the nutrients fresh.

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Appendices

Table 14. Mean total water yield for surface and tile by treatment for individual events and event total. Bold values denote a significant difference ($p \leq 0.05$) in mean values between cover and control treatments.

Event Date	Treatment	Total Flow (mm)	SD
3.28.16	Cover	6.7	4.7
	Control	7.1	0.7
4.7.16	Cover	11.0	7.0
	Control	11.5	4.4
4.11.16	Cover	8.3	6.9
	Control	4.5	1.5
6.4.16	Cover	3.0	1.8
	Control	4.6	1.6
6.28.16	Cover	0.4	0.4
	Control	0.3	0.4
7.9.16	Cover	0.2	0.0
	Control	0.2	0.3
7.18.16	Cover	0.1	0.0
	Control	0.1	0.1
8.14.16	Cover	0.3	0.4
	Control	0.2	0.0
8.28.16	Cover	1.7	1.0
	Control	1.8	0.5
10.20.16	Cover	14.2	9.8
	Control	11.6	4.0
2.20-2.24.17	Cover	**36.4**	9.6
	Control	**86.8**	17.9
2.25.17	Cover	8.9	2.5
	Control	10.0	4.2
3.27-3.29.17	Cover	68.0	49.7
	Control	103.3	60.3
4.2.17	Cover	**2.6**	2.0
	Control	**5.9**	3.1
4.6.17	Cover	22.5	9.7
	Control	19.1	7.7
6.29.17	Cover	14.1	7.9
	Control	12.8	6.3
Total	Sum Cover	**198.4**	17.5
	Sum Control	**279.7**	26.6

Table 15. Mean surface runoff by treatment for the 16 sampled events. Bold values denote a significant difference (*p*≤ 0.05) in mean values between cover and control treatments.

Event Date	Treatment	Surface Flow (mm)	SD
4.7.16	Cover	0.7	0.7
	Control	2.1	2.1
6.5.16	Cover	0.1	0.1
	Control	1.2	1.7
6.28.16	Cover	0.4	0.4
	Control	0.3	0.4
7.9.16	Cover	0.2	0.0
	Control	0.2	0.3
7.18.16	Cover	0.1	0.0
	Control	0.1	0.1
8.28.16	Cover	0.6	0.3
	Control	0.6	0.6
10.20.16	Cover	1.2	0.0
	Control	5.1	6.8
2.20-2.24	Cover	**36.4**	9.6
	Control	**86.8**	17.9
2.25.17	Cover	3.6	2.0
	Control	6.4	6.3
3.27-3.29	Cover	**65.3**	58.9
	Control	**100.4**	37.0
4.2.17	Cover	**2.6**	2.0
	Control	**5.9**	3.1
4.6.17	Cover	3.4	0.5
	Control	3.3	4.6
6.29.17	Cover	0.6	0.1
	Control	1.2	1.6
Total	Sum Cover	112.6	23.5
	Sum Control	207.7	36.1

Table 16. Mean Tile runoff by treatment for sampled events over the course of the study. Bold values denote a significant difference ($p \leq 0.05$) in mean values between cover and control treatments.

Event Date	Treatment	Tile Flow (mm)	SD
3.28.16	Cover	6.7	4.7
	Control	7.1	0.7
4.7.16	Cover	10.3	7.4
	Control	9.4	0.9
4.11.16	Cover	8.3	6.9
	Control	4.5	1.5
6.5.16	Cover	3.0	1.0
	Control	3.4	0.4
8.14.16	Cover	0.3	0.4
	Control	0.2	0.0
8.28.16	Cover	1.1	1.6
	Control	1.2	0.2
10.20.16	Cover	13.0	12.1
	Control	6.5	0.5
2.25.17	Cover	5.3	3.6
	Control	3.6	2.6
3.27-3.29	Cover	2.6	0.7
	Control	2.8	3.0
4.6.17	Cover	19.1	6.1
	Control	15.8	1.1
6.29.17	Cover	13.6	4.2
	Control	11.5	3.3
Total	Sum Cover	83.2	7.1
	Sum Control	66.1	4.8

Table 17. PSNT results for samples taken from plots over the course of the study.

PSNT (mg NO_3-N kg^{-1} Dry Soil)		
	Rye	Control
6/22/16	4.6	5.8
6/30/17	8.3	5.4
7/8/16	7.2	6.3
7/15/16	8.7	8.9
7/22/16	8.6	3.8
7/31/16	3.1	2.6
8/14/2016	1.0	2.4
8/21/2016	1.4	1.2
9/10/2016	1.1	1.2
10/20/2016	3.9	6.5
11/14/2016	1.1	1.2
5/11/2017	0.1	0.5
5/23/2017	1.5	0.8
6/8/2017	0.4	0.4
6/22/2017	2.7	1.7
7/12/2017	2.0	1.5
8/1/2017	2.4	1.2

Table 18. Phosphorus losses (TP and SRP) for every sampled event over the course of the study. Bold values denote a significant difference ($p \leq 0.05$) in mean values between cover and control treatments, an * indicates mean values were trending towards significance ($p \leq 0.10$).

Event Date	Treatment	SRP g-P/ha	SD	TP g-P/ha	SD
3.28.16	Cover	0.6	0.5	4.4	5.5
	Control	0.4	0.0	0.8	0.4
4.7.16	Cover	2.3*	1.4	**10.2**	5.4
	Control	2.0*	0.9	**4.5**	3.3
4.11.16	Cover	0.2	0.2	0.6	0.6
	Control	0.1	0.0	0.1	0.1
6.5.16	Cover	0.5	0.4	0.9	0.7
	Control	1.7	1.5	2.6	2.4
6.28.16	Cover	0.9	0.9	0.9	0.9
	Control	0.6	0.8	0.6	0.8
7.9.16	Cover	0.2	0.1	0.2	0.1
	Control	0.3	0.5	0.3	0.5
7.18.16	Cover	0.1	0.1	0.1	0.1
	Control	0.1	0.2	0.1	0.2
8.14.16	Cover	0.0	0.0	0.0	0.0
	Control	0.0	0.0	0.0	0.0
8.28.16	Cover	1.0	0.7	1.3	0.8
	Control	1.6	0.8	2.3	1.1
10.20.16	Cover	23.6	19.7	112.2	103.2
	Control	34.5	19.7	94.2	52.2
2.20-2.24	Cover	**232.5**	45.5	**252.9**	45.5
	Control	**706.3**	34.7	**816.9**	86.0
2.25.17	Cover	5.5	2.3	24.6	9.7
	Control	11.8	6.6	40.0	25.5
3.27-3.29	Cover	60.9	37.8	65.8	37.7
	Control	134.3	90.7	143.2	88.8
4.2.17	Cover	19.7*	13.8	**27.2**	21.5
	Control	66.1*	36.6	**76.8**	37.0
4.6.17	Cover	5.6	2.7	31.9	18.9
	Control	2.6	1.3	11.7	7.5
6.29.17	Cover	0.9	0.2	4.5	3.5
	Control	1.7	0.8	3.1	1.0
Total	Sum Cover	**334.7**	48.5	**510.4**	59.1
	Sum Control	**963.8**	144.2	**1197.3**	166.4

Table 19. Surface phosphorus losses for every sampled event over the course of the study. Bold values indicate significance (*p*≤ 0.05) in mean values between treatments, a * indicates mean values were trending towards significance (*p*≤ 0.10).

Event Date	Treatment	SRP g-P/ha	SD	TP g-P/ha	SD
4.7.16	Cover	0.2	0.3	0.7	0.6
	Control	0.9	1.0	0.8	2.1
6.5.16	Cover	0.0	0.1	0.1	0.0
	Control	1.6	2.2	2.5	0.3
6.28.16	Cover	**0.9**	0.9	**0.9**	0.2
	Control	**0.6**	0.8	**0.6**	0.2
7.9.16	Cover	0.2	0.1	0.2	0.0
	Control	0.3	0.5	0.3	0.0
7.18.16	Cover	0.1	0.1	0.1	0.0
	Control	0.1	0.2	0.1	0.0
8.28.16	Cover	**1.0**	0.8	1.2	0.0
	Control	**0.8**	0.8	1.0	0.0
10.20.16	Cover	2.4	2.8	4.8	0.2
	Control	20.2	27.5	48.9	8.2
2.20-2.24	Cover	**232.5**	45.5	**252.9**	0.5
	Control	**706.3**	34.7	**816.9**	4.1
2.25.17	Cover	**3.6**	2.6	10.7	0.3
	Control	**11.3**	3.4	35.5	7.7
3.27-3.29	Cover	**53.3**	46.8	**57.7**	0.1
	Control	**133.1**	85.3	**140.7**	0.1
4.2.17	Cover	19.7	13.8	**27.2**	0.5
	Control	66.1	36.6	**76.8**	3.0
4.6.17	Cover	2.0	1.4	6.6	1.1
	Control	1.4	1.9	2.4	0.3
6.29.17	Cover	0.3	0.0	0.5	26.5
	Control	1.0	1.3	1.2	13.7
Total	Sum Cover	**316.4**	64.4	**363.7**	10.0
	Sum Control	**943.7**	191.5	**1127.8**	15.0

Table 20. Tile Phosphorus losses for every sampled event over the course of the study. Bold values indicate significance (*p*≤ 0.05) in mean values between treatments, a * indicates mean values were trending towards significance (*p*≤ 0.10).

Event Date	Treatment	SRP g-P/ha	SD	TP g-P/ha	SD
3.28.16	Cover	0.6*	0.5	4.4	5.5
	Control	0.4*	0.0	0.8	0.4
4.7.16	Cover	**2.0**	1.7	**9.4**	3.2
	Control	**1.1**	1.3	**3.7**	4.8
4.11.16	Cover	0.2	0.2	0.6	0.6
	Control	0.1	0.0	0.1	0.1
6.5.16	Cover	0.4	0.5	0.8	1.0
	Control	0.1	0.1	0.1	0.1
8.14.16	Cover	0.0	0.0	0.0	0.0
	Control	0.0	0.0	0.0	0.0
8.28.16	Cover	0.0	0.1	0.0	0.1
	Control	0.8	1.1	1.3	1.7
10.20.16	Cover	21.1	28.5	107.3	146.4
	Control	14.3	19.3	45.3	60.5
2.25.17	Cover	1.9	2.5	13.9	13.8
	Control	0.4	0.4	4.5	5.5
3.27-3.29	Cover	7.6	2.8	8.1	2.1
	Control	1.2	0.9	2.6	0.9
4.6.17	Cover	**3.6**	4.2	**25.3**	26.9
	Control	**1.2**	1.2	**9.2**	10.5
6.29.17	Cover	0.5	0.4	4.0	5.0
	Control	0.7	0.0	1.9	0.2
Total	Sum Cover	38.0	8.8	174.0	44.7
	Sum Control	20.3	5.9	69.5	18.7

Table 21. TSS losses for each sampled event over the course of the study, Surface and Tile combined. Bold values indicate significance ($p \leq 0.05$) in mean values between treatments, a * indicates mean values were trending towards significance ($p \leq 0.10$).

Event Date	Treatment	TSS kg/ha	SD
3.28.16	Cover	1.4	1.5
	Control	0.3	0.2
4.7.16	Cover	0.5	0.4
	Control	1.9	1.7
4.11.16	Cover	0.1	0.0
	Control	0.1	0.1
6.5.16	Cover	0.0	0.0
	Control	0.2	0.2
6.28.16	Cover	0.5	0.2
	Control	0.1	0.2
7.9.16	Cover	0.1	0.0
	Control	0.0	0.0
7.18.16	Cover	0.0	0.0
	Control	0.0	0.0
8.14.16	Cover	0.0	0.0
	Control	0.0	0.0
8.28.16	Cover	0.1	0.0
	Control	0.2	0.2
10.20.16	Cover	4.6	3.8
	Control	7.8	5.4
2.20-2.24	Cover	2.6	0.5
	Control	5.3	4.1
2.25.17	Cover	0.7	0.3
	Control	6.5	5.8
3.27-3.29	Cover	0.5	0.1
	Control	0.4	0.2
4.2.17	Cover	0.7	0.5
	Control	2.8	3.0
4.6.17	Cover	2.3	1.1
	Control	0.6	0.3
6.29.17	Cover	0.4	0.3
	Control	0.2	0.0
Total	Sum Cover	13.7	1.3
	Sum Control	26.5	2.7

Table 22. Surface TSS losses for the study duration. Bold values indicate significance (*p*≤ 0.05) in mean values between treatments, a * indicates mean values were trending towards significance (*p* ≤ 0.10).

Event Date	Treatment	TSS kg/ha	SD
4.7.16	Cover	0.5	0.6
	Control	1.9	2.1
6.5.16	Cover	0.0	0.0
	Control	0.2	0.3
6.28.16	Cover	**0.5**	0.2
	Control	**0.1**	0.2
7.9.16	Cover	0.1	0.0
	Control	0.0	0.0
7.18.16	Cover	0.0	0.0
	Control	0.0	0.0
8.28.16	Cover	0.1	0.0
	Control	0.0	0.0
10.20.16	Cover	0.4	0.2
	Control	5.9	8.1
2.20-2.24	Cover	2.6	0.5
	Control	5.3	4.1
2.25.17	Cover	0.2	0.3
	Control	6.4	7.7
3.27-3.29	Cover	0.3	0.1
	Control	0.4	0.1
4.2.17	Cover	0.7	0.5
	Control	2.8	3.0
4.6.17	Cover	1.0	1.1
	Control	0.2	0.3
6.29.17	Cover	0.0	0.0
	Control	0.1	0.0
Total	Sum Cover	5.7	0.7
	Sum Control	20.6	3.5

Table 23. Tile TSS losses for the study duration. Bold values indicate significance (*p* ≤ 0.05) in mean values between treatments, a * indicates mean values were trending towards significance (*p* ≤ 0.10).

Event Date	Treatment	TSS kg/ha	SD
3.28.16	Cover	1.4	1.5
	Control	0.3	0.2
4.7.16	Cover	**0.0**	0.0
	Control	**0.0**	0.0
4.11.16	Cover	0.1	0.0
	Control	0.1	0.1
6.5.16	Cover	0.0	0.0
	Control	0.0	0.0
8.14.16	Cover	0.0	0.0
	Control	0.0	0.0
8.28.16	Cover	0.0	0.0
	Control	0.2	0.3
10.20.16	Cover	4.2	5.5
	Control	1.8	2.3
2.25.17	Cover	**0.5**	0.3
	Control	**0.1**	0.0
3.27-3.29	Cover	0.2	0.1
	Control	0.0	0.0
4.6.17	Cover	1.2	1.6
	Control	0.4	0.5
6.29.17	Cover	0.4	0.4
	Control	0.1	0.0
Total	Cover	8.0	1.8
	Control	3.0	0.7

Table 24. Nitrogen losses for both surface and tile drainage for every sampled event over the course of the study. Bold values indicate significance ($p \leq 0.05$) in mean values between treatments, a * indicates mean values were trending towards significance ($p \leq 0.10$).

Event Date	Treatment	Nitrate g-N ha^{-1}	SD	TN g-N ha^{-1}	SD
3.28.16	Cover	751.9	463.7	791.6	407.6
	Control	936.6	366.6	1137.3	497.2
4.7.16	Cover	936.0	589.5	1042.7	614.4
	Control	1475.6	900.1	1623.3	1062.9
4.11.16	Cover	1189.8	551.5	1656.5	775.3
	Control	1012.5	584.7	1431.0	882.0
6.5.16	Cover	410.1	242.5	497.9	288.9
	Control	735.7	408.8	955.5	573.6
6.28.16	Cover	9.1	7.3	15.0	10.1
	Control	6.1	8.6	10.2	14.4
7.9.16	Cover	4.8	1.0	4.8	1.0
	Control	3.8	5.4	8.2	11.5
7.18.16	Cover	1.4	0.1	1.8	0.1
	Control	1.4	2.0	1.9	2.6
8.14.16	Cover	62.3	0.4	0.0	0.0
	Control	42.3	19.4	0.0	0.0
8.28.16	Cover	0.0	0.0	0.0	0.0
	Control	0.0	0.0	0.0	0.0
10.20.16	Cover	2603.2	1786.2	2896.4	2006.3
	Control	753.4	454.6	1444.8	591.9
2.20-2.24	Cover	27.7*	16.8	**1310.5**	284.7
	Control	90.0*	28.4	**3922.1**	216.8
2.25.17	Cover	849.4	422.6	926.6	382.9
	Control	797.3	475.0	1065.4	371.1
3.27-3.29	Cover	297.4	149.0	630.2	151.5
	Control	809.8	454.7	1225.0	448.7
4.2.17	Cover	*100.9*	55.0	*232.2*	151.5
	Control	*248.8*	148.8	*553.7*	339.7
4.6.17	Cover	5268.3	2927.9	5651.5	3082.4
	Control	4895.7	2762.8	5012.9	2810.4
6.29.17	Cover	3201.8	1842.2	3223.7	1851.4
	Control	3074.6	1754.1	3107.4	1761.7
Total	Sum Cover	15714.2	1287.2	18881.2	1364.5
	Sum Control	14883.7	144.2	21498.6	1330.8

Table 25. Nitrogen losses from surface runoff for every sampled event over the course of the study. Bold values indicate significance ($p \leq 0.05$) in mean values between treatments, a * indicates mean values were trending towards significance ($p \leq 0.10$).

Event Date	Treatment	Nitrate g-N/ha	SD	TN g-N/ha	SD
4.7.16	Cover	11.0	9.1	11.0	9.1
	Control	39.5	42.3	33.1	33.3
6.5.16	Cover	1.3	1.8	1.5	2.2
	Control	26.1	36.9	27.2	38.4
6.28.16	Cover	9.1	7.3	15.0	10.1
	Control	6.1	8.6	10.2	14.4
7.9.16	Cover	4.8	1.0	4.8	1.0
	Control	3.8	5.4	8.2	11.5
7.18.16	Cover	1.4	0.1	1.8	0.1
	Control	1.4	2.0	1.9	2.6
8.28.16	Cover	0.0	0.0	0.0	0.0
	Control	0.0	0.0	0.0	0.0
10.20.16	Cover	7.4	0.0	39.5	43.0
	Control	82.1	93.4	494.8	666.3
2.20-2.24	Cover	27.7*	16.8	**1310.5**	284.7
	Control	90.0*	28.4	**3922.1**	216.8
2.25.17	Cover	65.9	34.0	143.1	100.1
	Control	11.5	16.1	279.5	282.5
3.27-3.29	Cover	**97.0**	48.2	**324.0**	143.1
	Control	**220.5**	55.2	**636.2**	235.3
4.2.17	Cover	100.9*	55.0	232.2*	151.5
	Control	248.8*	148.8	553.7*	339.7
4.6.17	Cover	119.7	11.8	157.7	38.7
	Control	55.5	77.5	74.4	103.7
6.29.17	Cover	14.6	17.9	17.1	17.0
	Control	18.3	25.9	28.4	39.7
Total	Sum Cover	460.9	46.4	**2258.1**	357.8
	Sum Control	803.7	91.2	**6069.6**	1057.2

Table 26. Nitrogen losses from tile drainage for every sampled event over the course of the study. Bold values indicate significance ($p \leq 0.05$) in mean values between treatments, a * indicates mean values were trending towards significance ($p \leq 0.10$).

Event Date	Treat-ment	Nitrate g-N/ha	SD	TN g-N/ha	SD
3.28.16	Cover	751.9	463.7	791.6	407.6
	Control	936.6	366.6	1137.3	497.2
4.7.16	Cover	925.0	455.0	1031.7	301.0
	Control	1436.2	691.4	1590.2	981.4
4.11.16	Cover	1189.8	551.5	1656.5	775.3
	Control	1012.5	584.7	1431.0	882.0
6.5.16	Cover	**408.8**	101.9	496.4	73.8
	Control	**709.6**	181.6	928.3	416.6
8.14.16	Cover	62.3	88.1	0.0	0.0
	Control	42.3	19.4	0.0	0.0
8.28.16	Cover	0.0	0.0	0.0	0.0
	Control	0.0	0.0	0.0	0.0
10.20.16	Cover	2595.8	1694.6	2856.9	2033.8
	Control	671.4	513.7	950.0	632.4
2.25.17	Cover	783.5	140.4	783.5	140.4
	Control	785.9	277.5	785.9	277.5
3.27-3.29	Cover	200.4	231.5	306.2	219.1
	Control	589.3	693.8	588.8	739.2
4.6.17	Cover	5148.6	654.0	5493.8	165.8
	Control	4840.2	15.9	4938.5	155.0
6.29.17	Cover	3187.2	339.6	3206.6	332.1
	Control	3056.2	31.2	3078.9	63.3
Total	Cover	15253.3	1633.9	16623.2	1732.0
	Control	14080.0	1432.165	15429.0	1461.7

Table 27. Winter Rye yields for each sample date for 2016 and 2017

Sample Date	Dry Bio-mass (kg/ha)
5.10.16	900.8
5.17.16	1614.3
5.22.16	2509.4
5.18.17	1688.8
5.23.17	2346.3
6.1.17	4436.3
6.7.17	5001.9